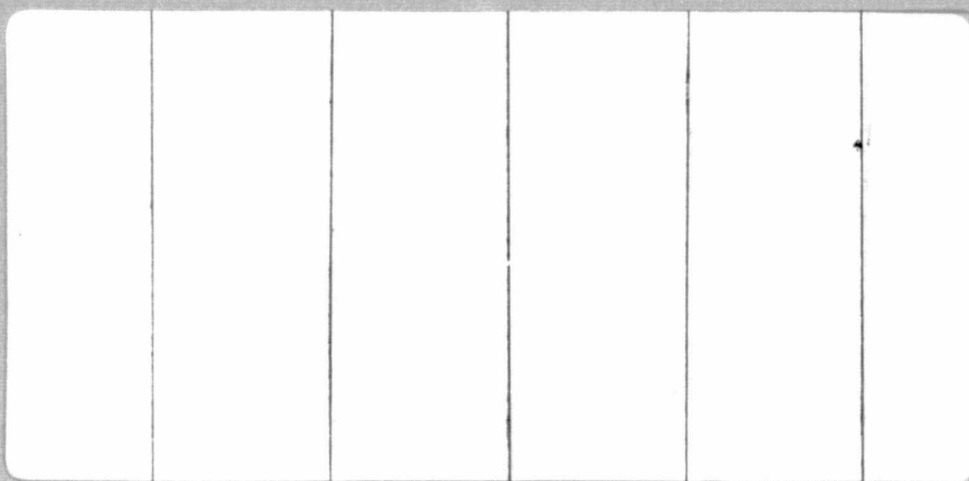


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(NASA-CR-143106) INVESTIGATION OF THE
DIFFICULTIES ASSOCIATED WITH THE USE OF LEAD
TELLURIDE AND OTHER II - IV COMPOUNDS FOR
THIN FILM THERMISTORS Final Report, Jan.
1970 - May 1975 (Tennessee Technological

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Engineering Complex



TENNESSEE TECHNOLOGICAL UNIVERSITY
COOKEVILLE, TENNESSEE

Investigation of the Difficulties Associated with the
Use of Lead Telluride and Other II - IV
Compounds for Thin Film Thermistors

Final Report Under Grant
NGR 43-003-012

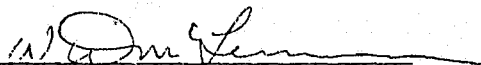
For the Period
January 1970 through May 1975

to

National Aeronautics and Space Administration
Langley Research Center
Langley Station
Hampton, Virginia 23365

from

Electrical Engineering Department
Tennessee Technological University
Cookeville, Tennessee 38501

A handwritten signature in dark ink, appearing to read 'W. D. McLennan', is written over a horizontal line.

W. D. McLennan
Principal Investigator

INTRODUCTION

This is the final technical report under NASA Grant NGR 43-003-C12. This research has been concerned with solving the difficulties associated with the fabrication of a thin film thermistor for use as an atmospheric temperature sensor in the meteorological rocket sounding program. The NASA Technical Officer for this grant was Mr. Charles Hardesty at NASA's Langley Research Center. This report covers the period from January 1970 to May 1975.

THE THIN FILM THERMISTOR

STRUCTURE

A number of sensing materials and device structures were considered in the course of this investigation. The final configuration is shown in Fig. 1 and consists of six (6) layers of material which were vacuum deposited on a kapton* substrate 0.00025 inches thick. Two of these six layers were deposited on the back surface with the remaining four layers being deposited on the front surface. The composition of the six layers, their primary function, and appropriate comments are contained in the following list. (The numbers in parenthesis refers to Fig. 1)

- (1) Quartz (SiO_2) - When quartz is deposited on a kapton substrate the stresses in the quartz film will cause the substrate to curl. This layer produces forces which counteract the forces produced by the quartz layers deposited on the front surface and therefore prevent the tendency for the substrate to curl.

* Kapton is a duPont tradename (1)

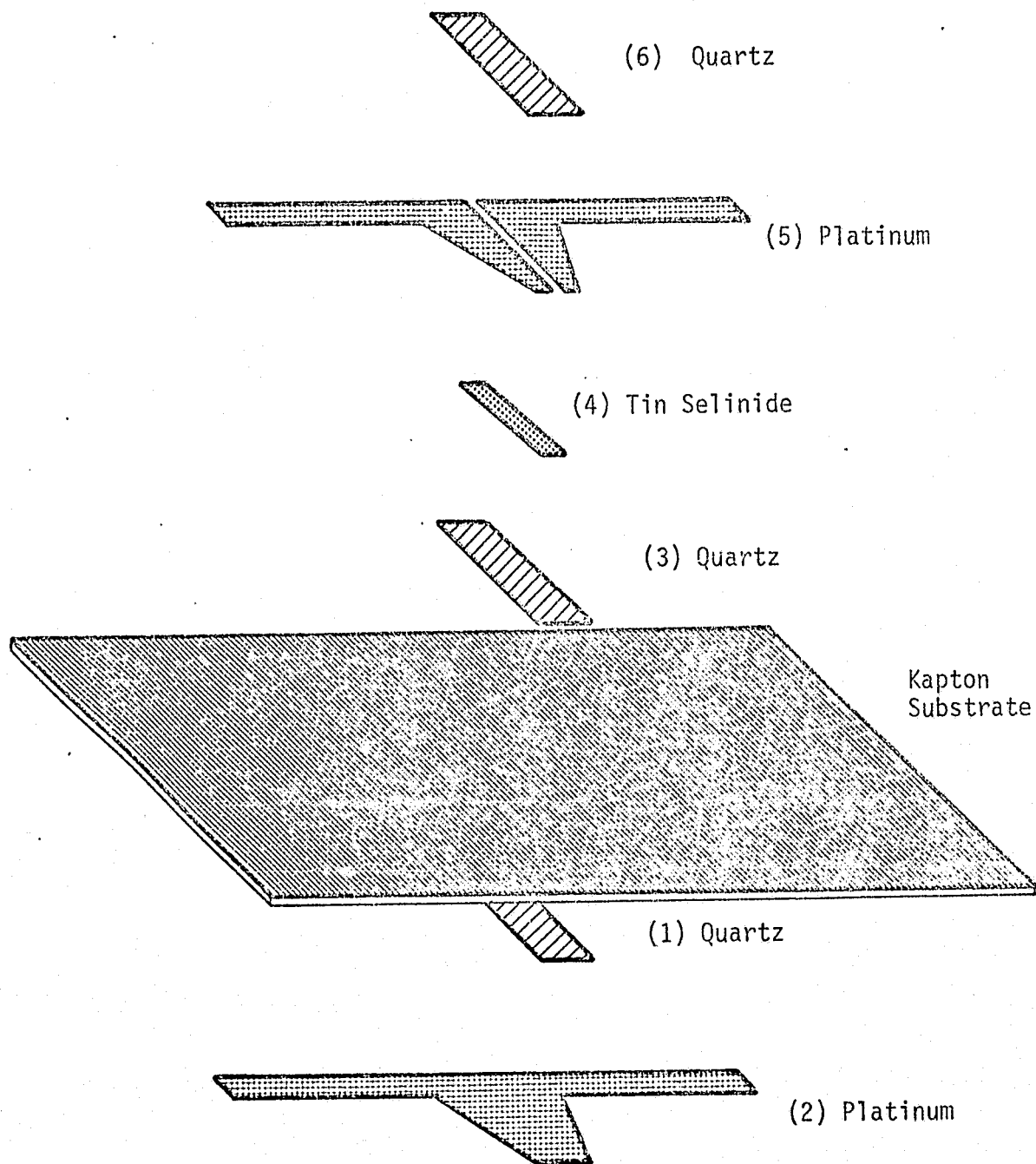


Figure 1. Thin film thermistor structure

- (2) Platinum (Pt) - This platinum layer has the same size and shape as the device deposited on the front side of the kapton and acts as a radiation shield.
- (3) Quartz (SiO_2) - The function of this layer is to isolate the sensing material from the kapton substrate. That is, it serves as the lower half of an encapsulating layer surrounding the sensing material. The need for and the effect of this layer was discussed in the 7th semi annual status report which covered the research period, December 1, 1972 through May 31, 1973.
- (4) Tin Selenide (SnSe) - This is the sensing material. Tin selenide was one of the six compound semiconductors considered. The other five were the compounds of tin with tellurium and sulfur and the compounds of lead with selenium, tellurium, and sulfur. The initial phase of this development effort concentrated on the use of lead telluride as the sensing material because it had a lower resistance at room temperature than the tin selenide. However, the problem of migration between the lead telluride and the metal contacts could not be solved and the effort was shifted to tin selenide.
- (5) Platinum (Pt) - The ratio of the electrical conductivity to the thermal conductivity is larger for platinum than for any other metal. For this reason platinum was chosen for the electrical contacts since it was necessary to thermally isolate

the sensing region of the device from the supporting shield.
the actual sensing area of the thin film thermistor is
defined by a 0.010 inch gap between the two contact pads.

- (6) Quartz (SiO_2) - This last layer of quartz serves as the second half of the encapsulation and protects the sensing region from moisture and other contaminants.

FABRICATION

The six layers of material which form the thermistor were vacuum deposited from source material which was heated by means of an electron gun. The chamber pressure prior to the start of the deposition process was less than 10^{-7} Torr and increased into the high 10^{-6} or low 10^{-5} Torr range during the deposition. Since the kapton substrate was not self-supporting, it had to be wrapped around a 2 inch square glass substrate for support with a second substrate used to clamp the ends of the kapton. After the quartz and platinum layers had been deposited on the back side of the kapton, the sample had to be removed from the vacuum chamber and the kapton turned over.

The metal masks used to define the patterns needed for the simultaneous deposition of three identical devices were etched from 0.005 inch thick berillium copper shim stock using photo masking techniques. The 0.01 inch gap which defined the sensing region was produced by spot welding a 0.01 inch tungsten wire to the previously etch contact mask.

This resulted in a gap which defined the sensing region which had a uniform width and smoother edges than could be obtained with photo etching techniques.

The six layers which make up the device were deposited under the control of a minicomputer. A dissertation describing this controller and its capabilities is included as appendix I of this report. For further information on the fabrication process the reader is referred to appendix I of the 10th semi annual report.

TESTING

A constant temperature chamber was designed and constructed for use in calibrating the sensors at discrete temperatures. The construction of this chamber is illustrated in Fig. 2. A container, to hold the liquids used for the constant temperature baths was constructed of one inch thick bakelite. This container was sealed with silicone seal, surrounded on all sides by at least four inches of styrofoam, and inserted in an aluminum box which opened at the middle to permit access to the inner sample enclosure. The samples to be tested along with two platinum resistance reference thermometers were mounted in a copper enclosure which is supported from the top of the bakelite container. Electrical connections from the samples and reference thermometers pass through feedthroughs in the top of the copper enclosure and are then routed through a stainless steel tube which passes through the cooling bath.

In order to fit the resistance vs. temperature characteristics of the sensors to an equation of the form

$$\frac{1}{T} = A + B \log R + C (\log R)^3 \quad (1)$$

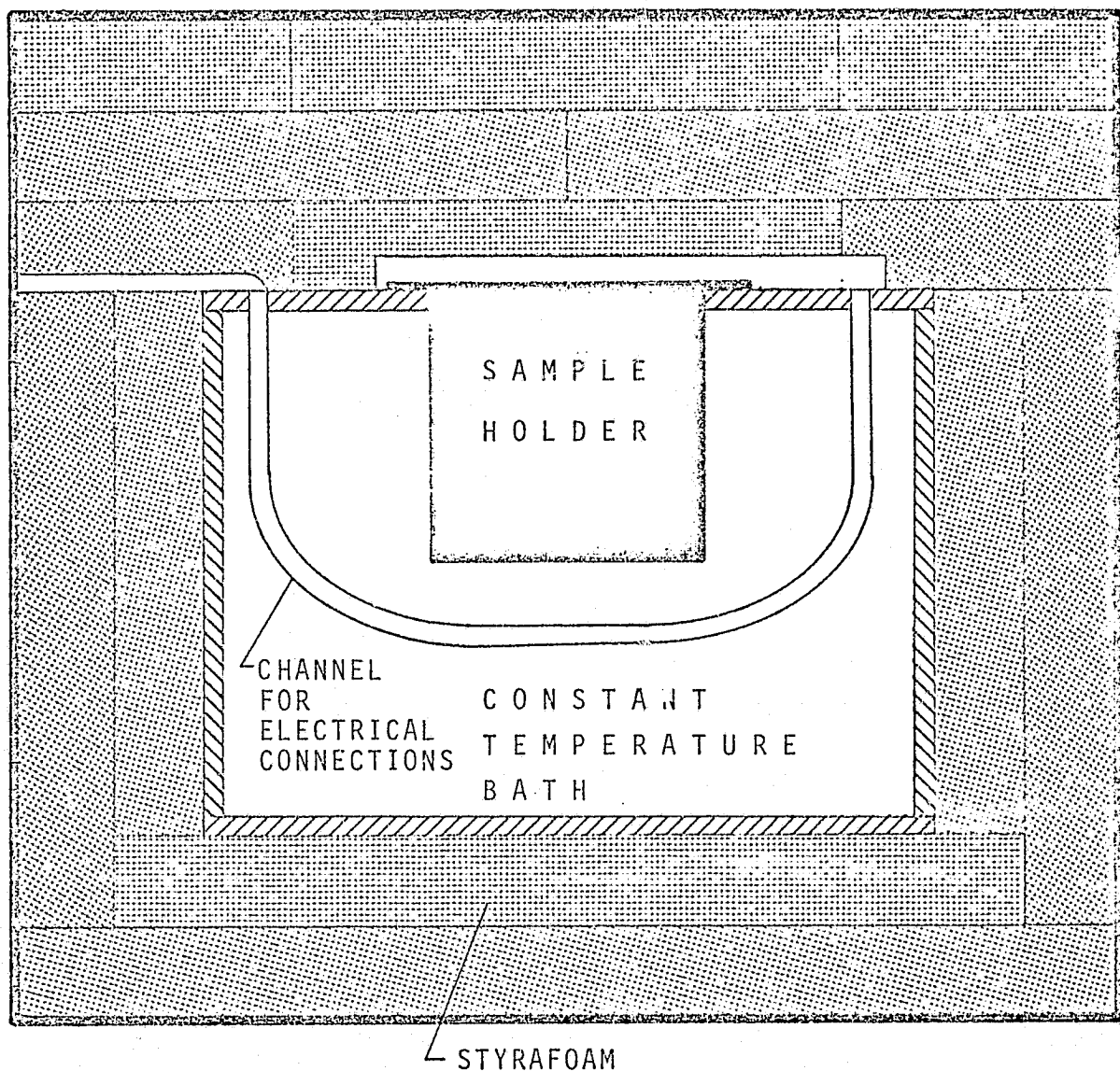


Figure 2. Illustration of constant temperature chamber construction.

data at three discrete temperatures was required. The temperature of a distilled ice water bath and the temperature of an acetone and dry ice bath were selected for two of these temperatures. Efforts to obtain a temperature bath having a temperature between these two were unsuccessful and therefore the room temperature in the laboratory was used for the third temperature.

During the measurement sequence the samples were sealed in the test chamber and measurements made at 5 minute intervals. Platinum resistance thermometer (PRT) FL-31 was arbitrarily selected as the standard for all subsequent comparisons. The resistance readings of a second PRT, FL-51, vs PRT FL-31 are shown in Fig. 3. These measurements indicate that the two PRTs are within 0.01 Centergrade degrees of each other for this group of measurements. The resistance of three representative thin film samples at room temperatures vs the resistance of PRT FL-31 are presented in Fig. 4. Based on this data, the resistance of PRT FL-31 which corresponded to 19°C was selected for one of the calibration points for the thin film samples. After the measurements at room temperature were completed, the copper container was surrounded with a distilled ice water bath and subsequently an acetone and dry ice bath. The resistance measurements at the three temperatures are given in Table 1.

After the chamber had been maintained at the temperature of the acetone and dry ice bath for two and a half days the temperature was allowed to increase. The difference in temperature between PRT FL-31 and PRT FL-51 as a function of the temperature of PRT FL-31, as the temperature of the box is returning to room temperature, is shown in Fig. 5. The spike

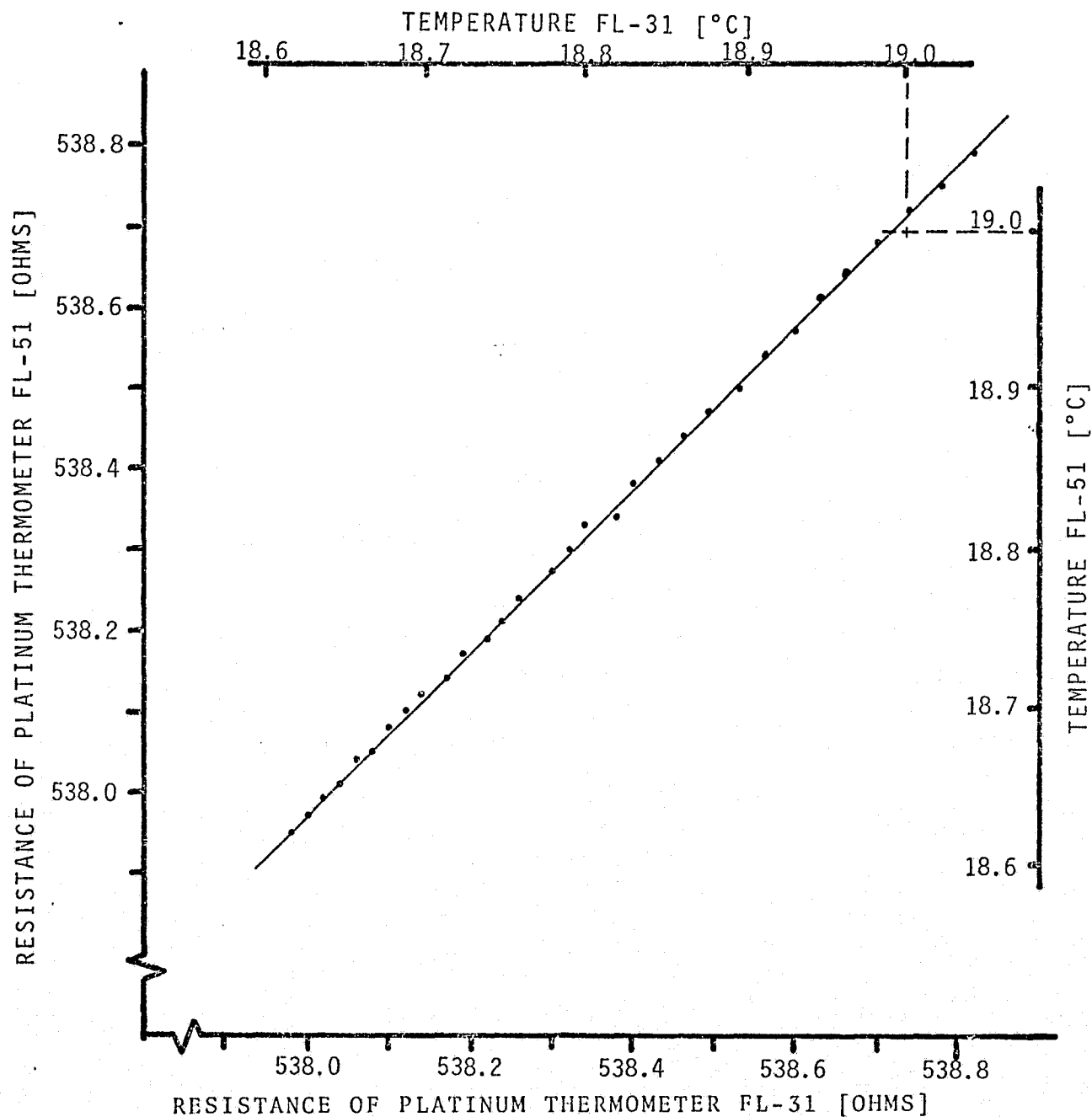


Figure 3. Comparison of the two platinum resistance thermometers (PRT) at room temperatures.

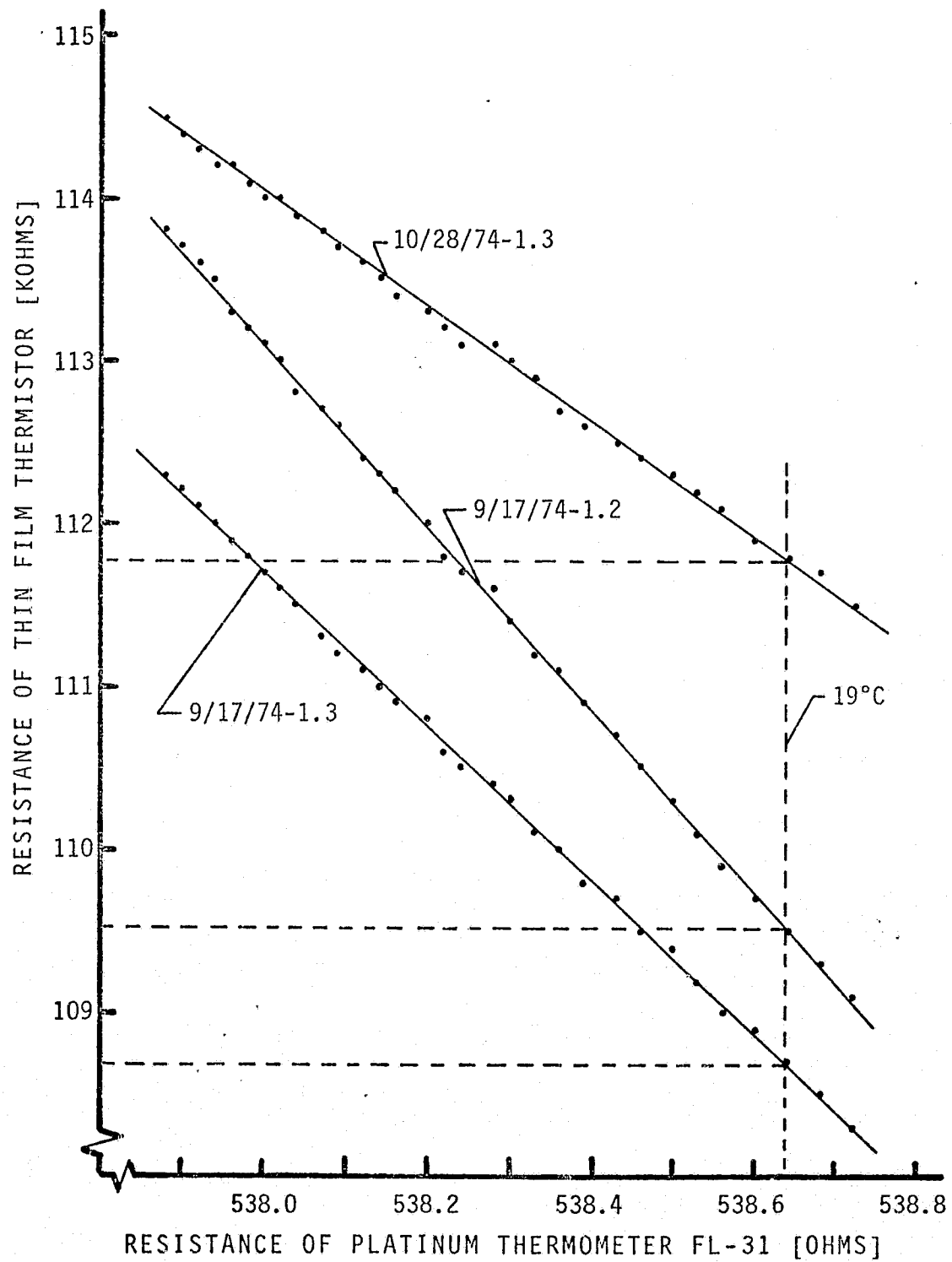


Figure 4. The resistance of three representative thin film thermistors as a function of the resistance of PRT FL-31.

TABLE 1

SAMPLE NUMBER	SAMPLE RESISTANCE [OHMS]		
	292.15°K	273.13°K	194.575°K
9/17/74-1.3	108,680	209,650	5,768,250
10/28/74-1.3	111,800	211,700	4,239,400
9/17/74-1.2	109,560	212,000	6,298,800
10/28/74-1.2	32,690	45,700	4,249,300
10/27/74-1.3	142,670	248,950	2,674,800
8/25/74-1.3	140,900	314,800	6,528,350
8/28/74-1.3	194,230	366,800	7,626,050

Measured resistance of thin film samples at selected calibration temperatures. (Data used for first set of computations)

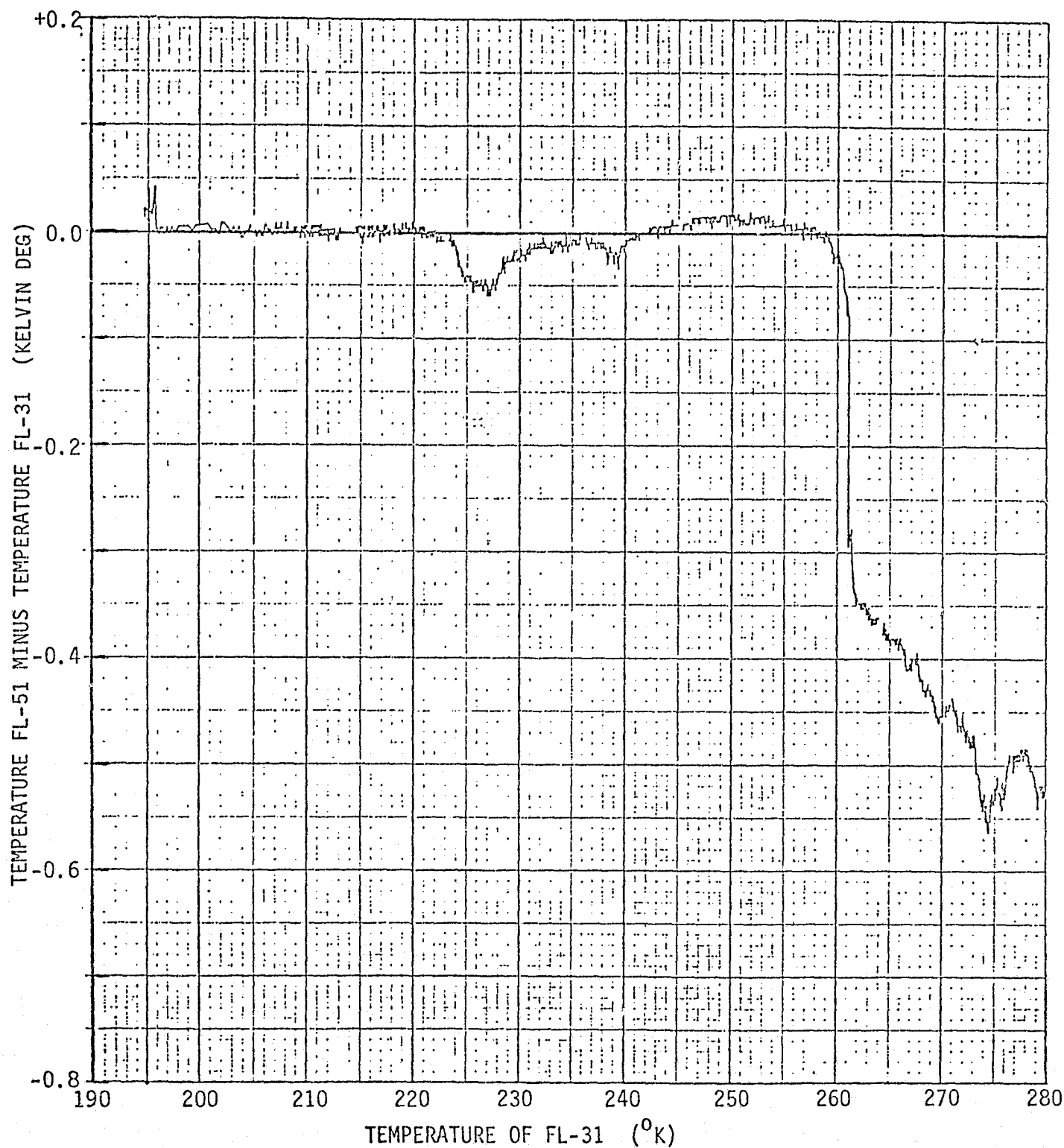


Figure 5. Difference in temperature between two platinum resistance reference thermometers as the chamber temperature is increasing. (Elapsed time is five (5) days)

on the curve at 195°K occurred when additional dry ice was added to the bath. The result drawn from this curve is that the two PRTs were in agreement when the temperature of the chamber was fairly stable.

Using equation 1 and the data in Table 1 the three coefficients for each thin film sample were calculated. These values are given in Table 2. Efforts to correlate the data obtained from the thin-film thermistors with the data obtained from the PRT were not, at first, completely satisfactory. Figure 6 shows the temperature of PRT FL-31 vs. time. This curve is of value as a basis for evaluating the subsequent thin film thermistor curves. The results obtained from the thin film samples fall into three classes.

I. 10/28/74-1.3 Fig. 7

10/27/74-1.3 Fig. 8

These curves are in reasonable agreement with PRT FL-31, however, there appears to be an offset error.

II. 10/28/74-1.2 Fig. 9

These results are not satisfactory. Part of the problem might be due to improper coefficients. Subsequent measurements and calculations show that this is the case.

III. 9/17/74-1.3 Fig. 10

9/17/74-1.2 Fig. 11

8/28/74-1.3 Fig. 12

These samples show a continuous drift in resistance and therefore there is no possibility of calibrating them until their characteristics stabilize.

TABLE 2

SAMPLE NUMBER	COEFFICIENTS FOR EQUATION 1 [$^{\circ}\text{K}^{-1}$]		
	A	B	C
9/17/74-1.3	1.0159×10^{-3}	1.3614×10^{-4}	5.3225×10^{-7}
10/28/74-1.3	1.9511×10^{-3}	1.2803×10^{-5}	8.4226×10^{-7}
9/17/74-1.2	8.1822×10^{-4}	1.6161×10^{-4}	4.6675×10^{-7}
10/28/74-1.2	-9.0988×10^{-3}	1.4397×10^{-3}	-2.1757×10^{-6}
10/27/74-1.3	4.4188×10^{-3}	-3.2286×10^{-4}	1.6964×10^{-6}
8/25/74-1.3	4.4646×10^{-3}	-2.6194×10^{-3}	1.2385×10^{-6}
8/28/74-1.3	1.7761×10^{-3}	2.4243×10^{-5}	7.4857×10^{-7}

Coefficients for equation 1 for each of the seven samples based on the data contained in Table 1. (Data used for first set of computations)

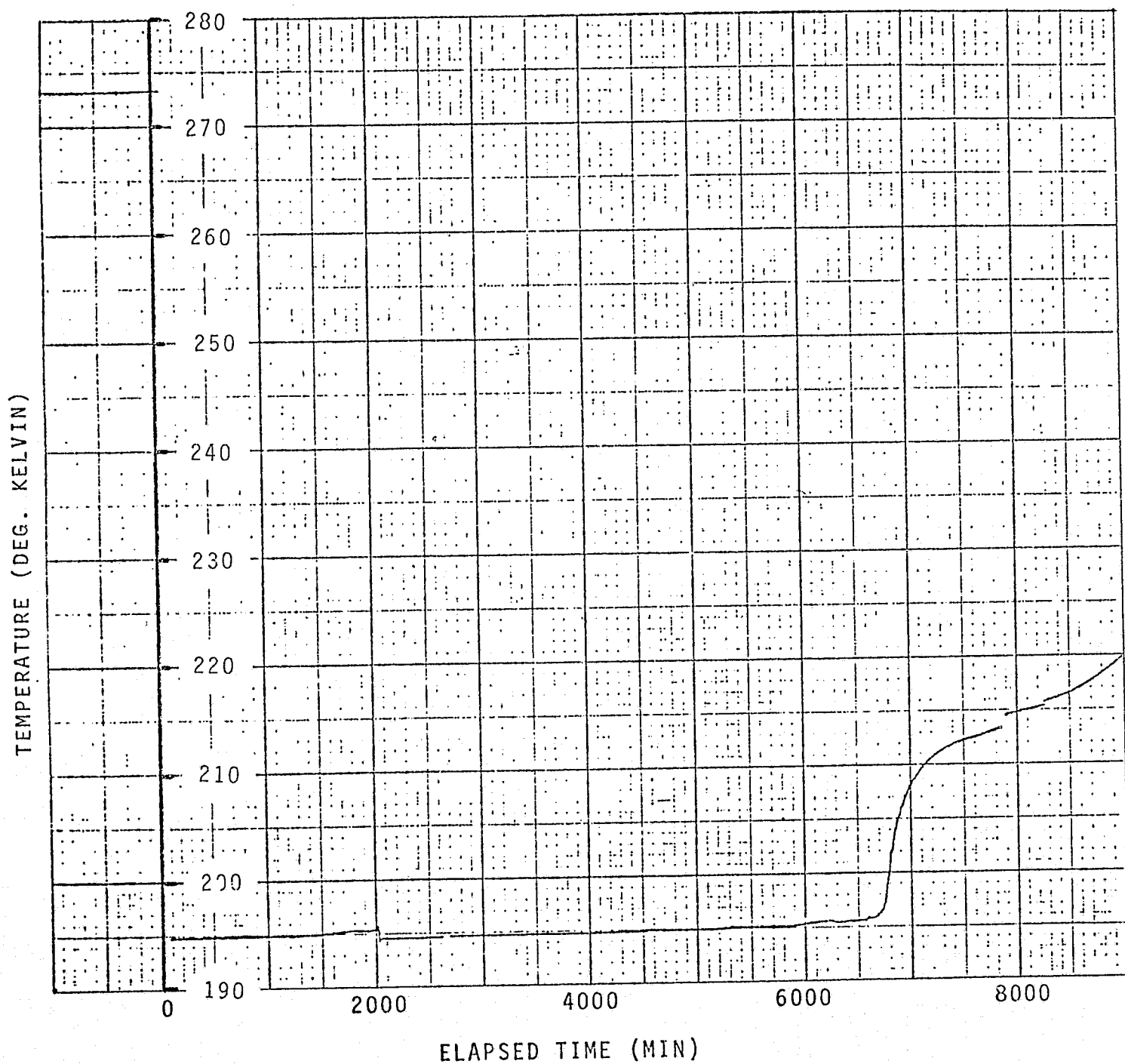


Figure 6. Plot of the temperature of PRT FL-31 as a function of elapsed time.

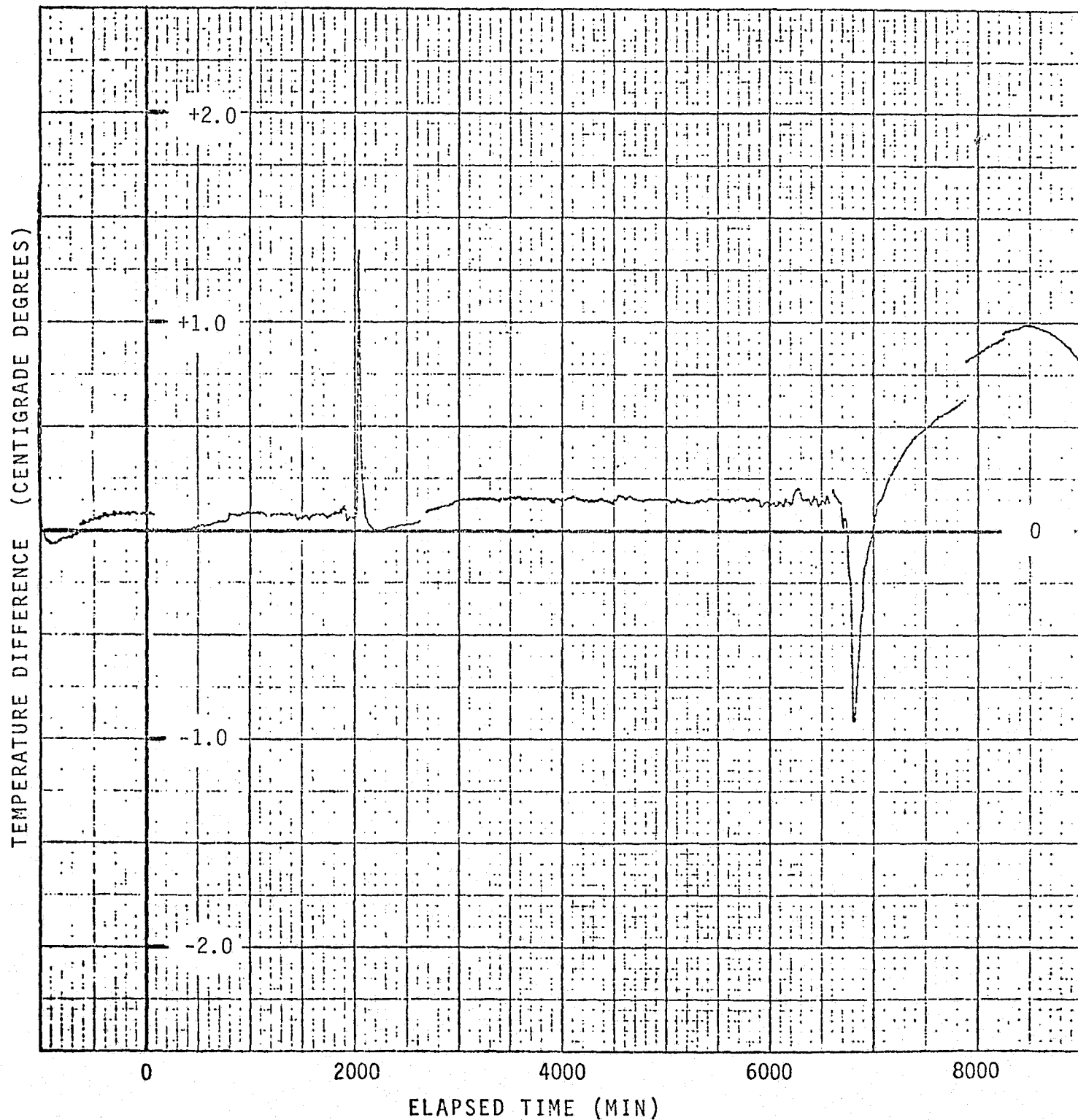


Figure 7. Plot of the difference in temperature between thin film sample 10/28/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2

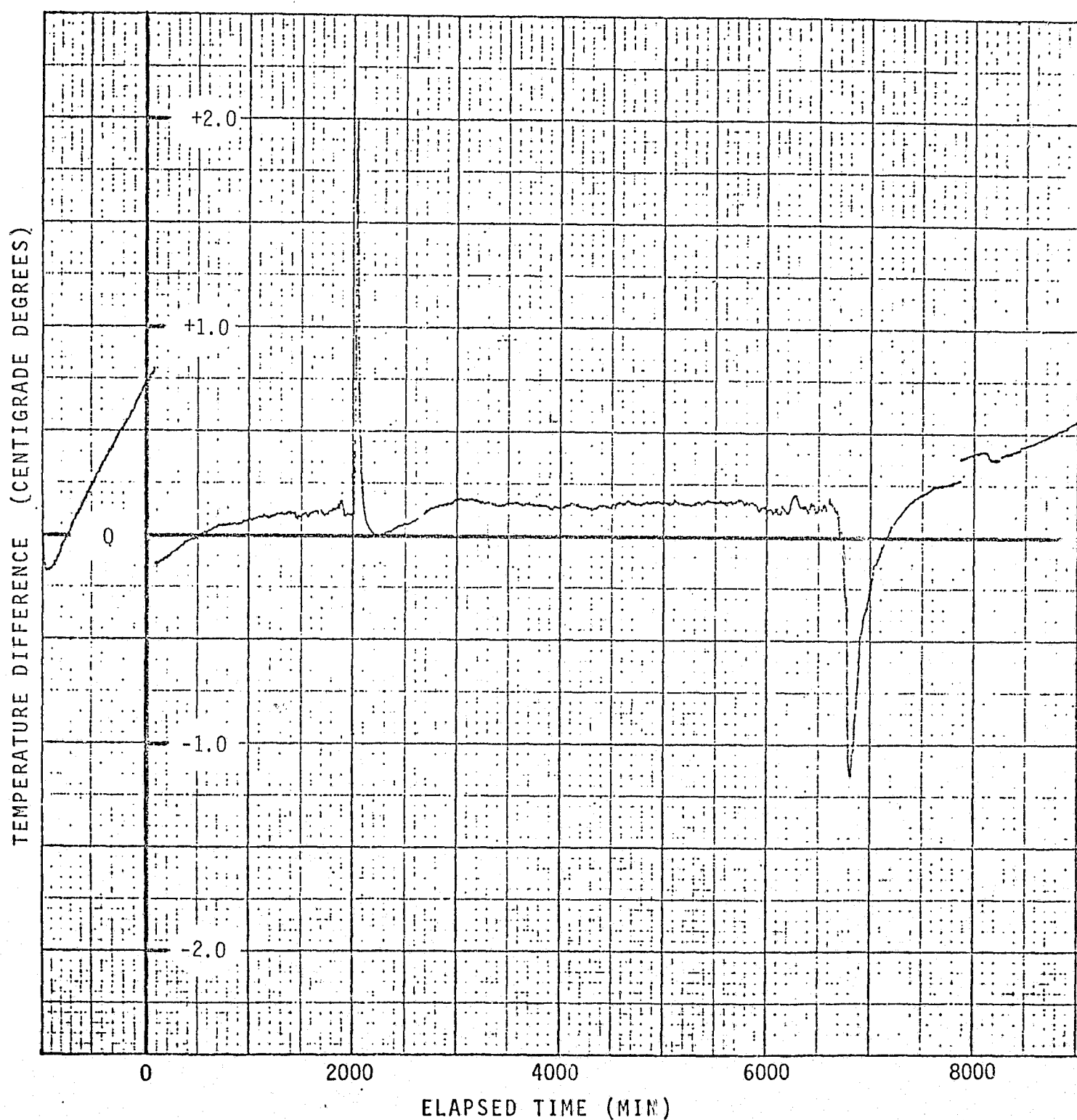


Figure 8. Plot of the difference in temperature between thin film sample 10/27/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

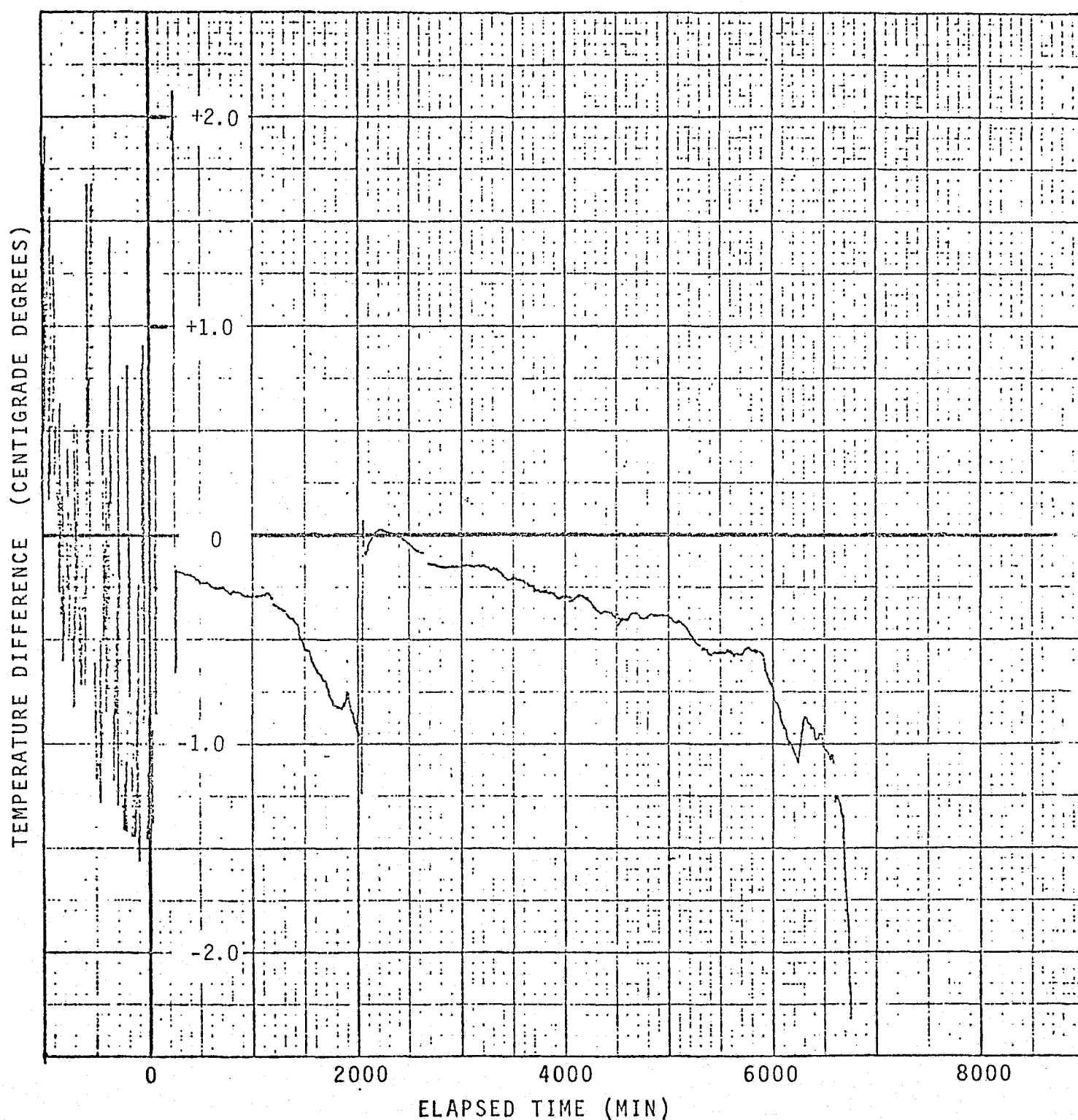


Figure 9. Plot of the difference in temperature between thin film sample 10/28/74-1.2 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

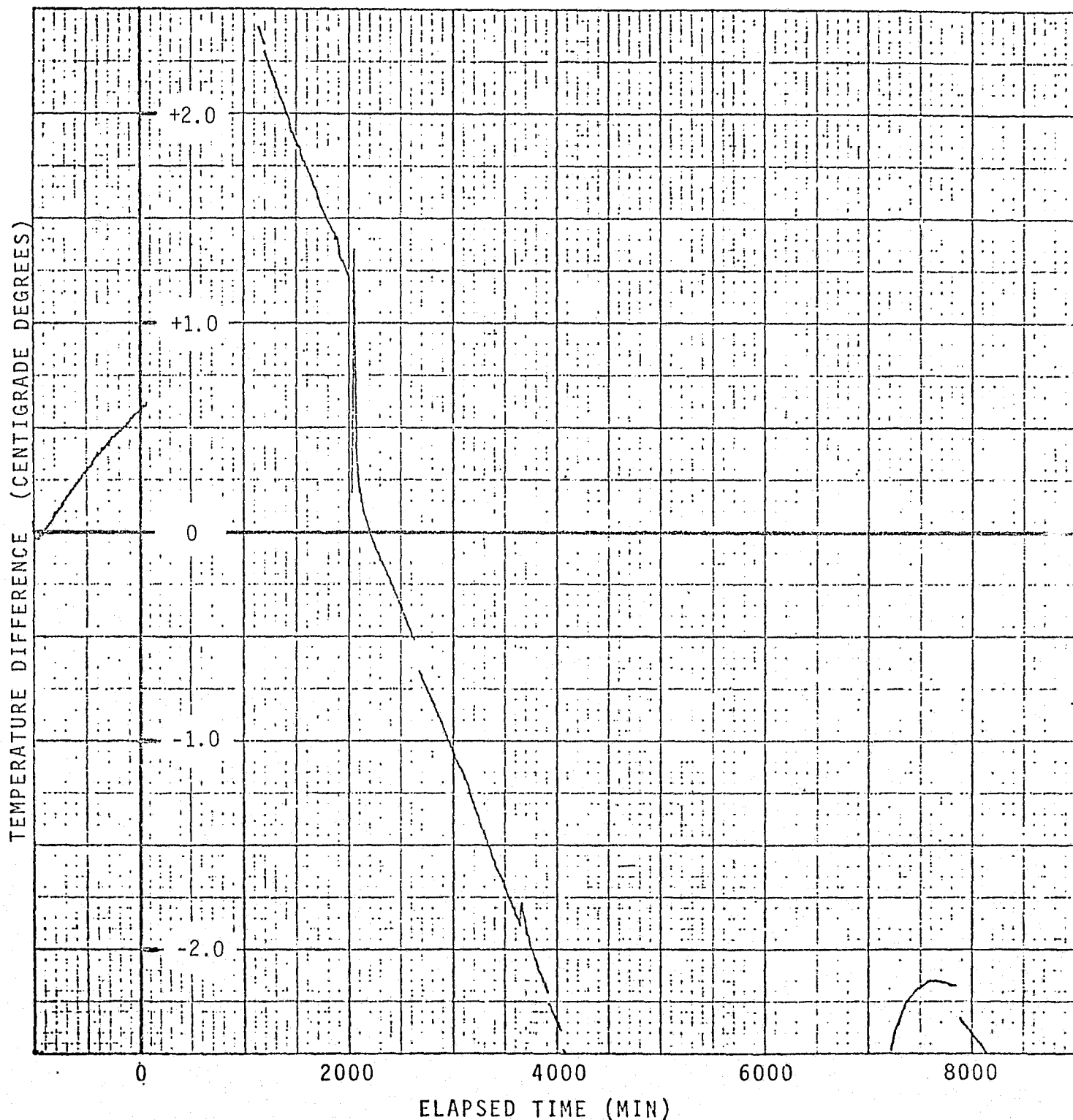


Figure 10. Plot of the difference in temperature between thin film sample 9/17/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

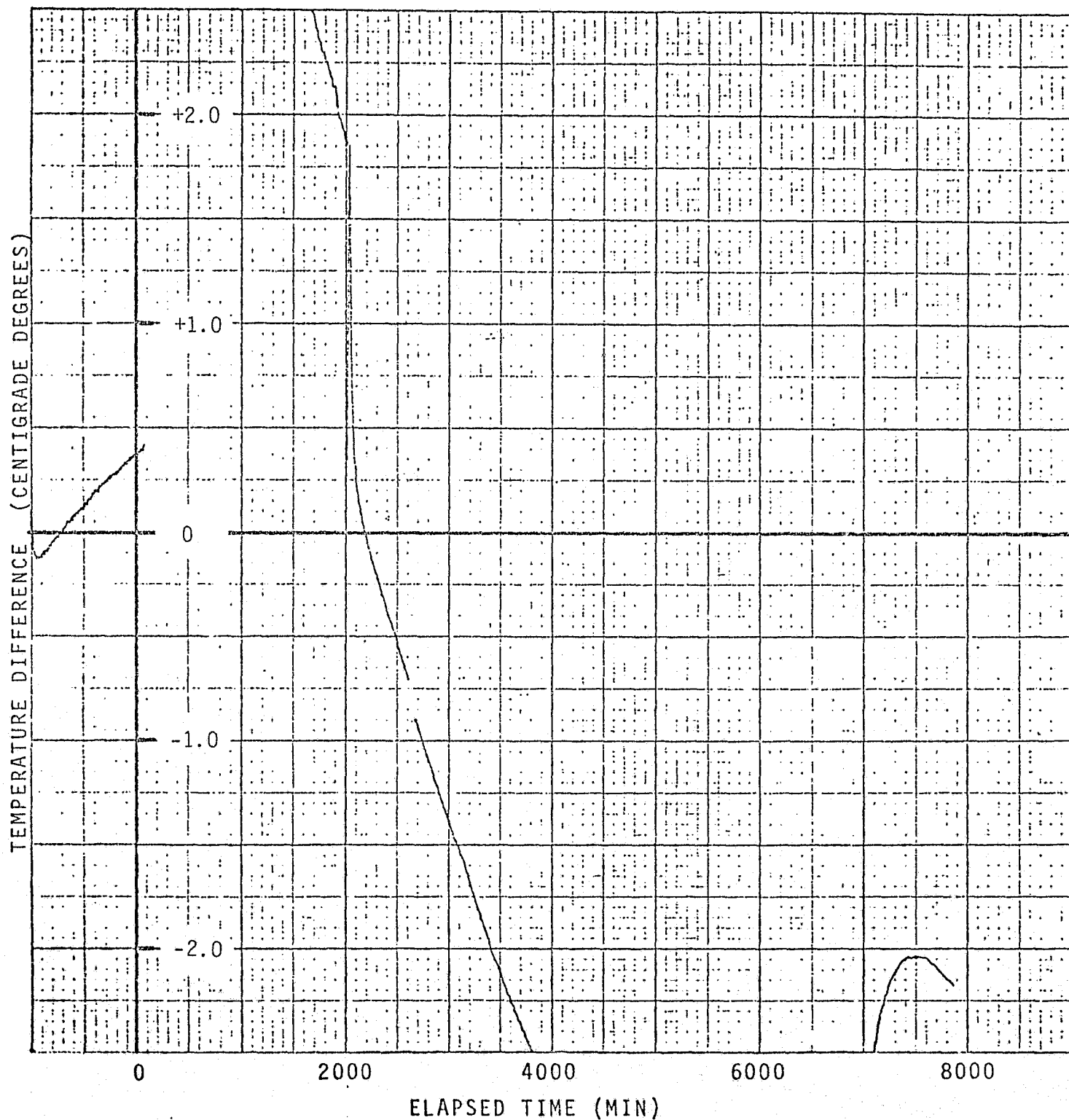


Figure 11. Plot of the difference in temperature between thin film sample 9/17/74-1.2 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

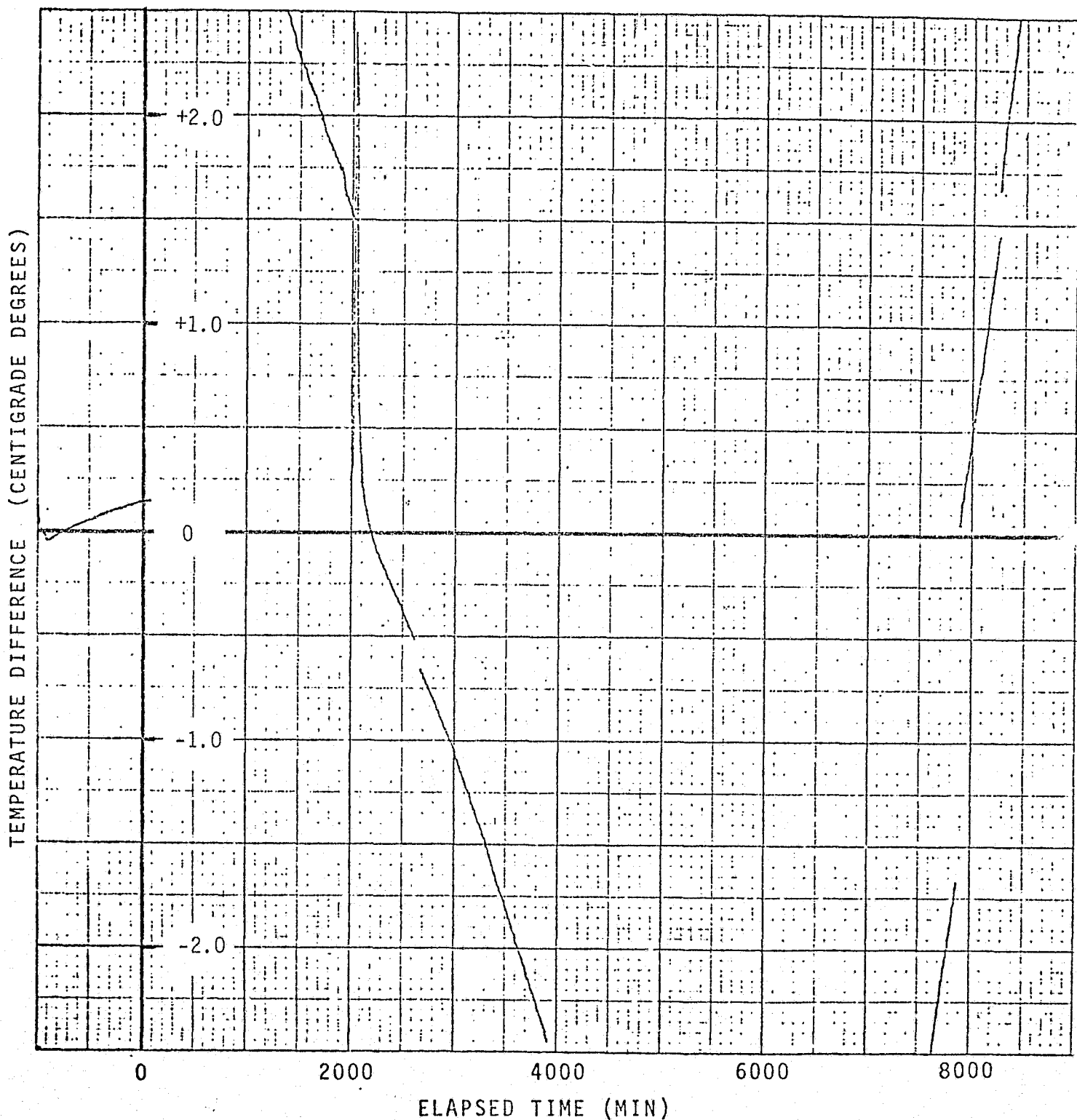


Figure 12. Plot of the difference in temperature between thin film sample 8/28/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

The sample numbers indicated above correspond to the date the sample was deposited. With this amount of elapsed time between fabrication and testing they should have stabilized.

When the samples returned to room temperature following this series of measurements it was noted that their resistance had changed. Another set of measurements were then made at room temperature and at the distilled ice water temperature. The resistance vs. temperature results obtained from this new set of measurements is shown in Table 3 and the corresponding coefficients for eq. 1 are shown in Table 4. In arriving at these new values the temperature of the chamber was allowed to stabilize, in each case, for two days before acquiring the data used for these calculations.

Figures 13, 14, and 15 show the room temperature results obtained for the three samples shown in Fig. 4. Note that, although the temperature range is slightly different, both sets of data include the temperature 19°C . After the chamber had been allowed to stabilize in the distilled ice water bath, the variations in PRTs FL-31 and FL-51 were less than ± 1 count which corresponds to $\pm 0.01^{\circ}\text{C}$ over a seven hour period. For the acetone and dry ice calibration point, referring to Figs. 7 and 8 and the data print-out, an extended period of time was selected during which the temperature of the samples appeared to be stable.

Using these new coefficients the data presented in Figs. 7-12 was again plotted. These results are presented in Figs. 16, 17, 18, and 19. Since the earlier data obtained at 273°K were inconsistent with these later

TABLE 3

SAMPLE NUMBER	SAMPLE RESISTANCE [OHMS]		
	273.07°K	292.15°K	194.72°K
9/17/74-1.3	503,450	552,600	6,084,450
10/28/74-1.3	257,350	188,010	4,190,200
9/17/74-1.2	261,000	223,940	6,780,000
10/28/74-1.2	263,800	193,770	4,203,200
10/27/74-1.3	356,250	280,900	2,649,550
8/25/74-1.3	388,300	299,180	6,408,200
8/28/74-1.3	593,650	524,360	8,005,000

Measured resistance of thin film samples at selected calibration temperatures. (data used for second set of computations)

TABLE 4

SAMPLE NUMBER	COEFFICIENTS FOR EQUATION 1 [$^{\circ}\text{K}^{-1}$]		
	A	B	C
9/17/74-1.3	1.8089×10^{-1}	-1.8907×10^{-2}	3.1373×10^{-5}
10/28/74-1.3	-1.2861×10^{-2}	1.6195×10^{-3}	-1.8892×10^{-6}
9/17/74-1.2	-4.6394×10^{-2}	5.2622×10^{-3}	-8.0276×10^{-6}
10/28/74-1.2	-1.3428×10^{-2}	1.6774×10^{-3}	-1.9784×10^{-6}
10/27/74-1.3	-2.1480×10^{-2}	2.4606×10^{-3}	-3.0220×10^{-6}
8/25/74-1.3	-2.0985×10^{-2}	2.4296×10^{-3}	-3.1062×10^{-6}
8/28/74-1.3	-7.6558×10^{-2}	8.1170×10^{-3}	-1.1785×10^{-5}

Coefficients for equation 1 for each of the seven samples based on the data contained in Table 3. (Data used for second set of computations)

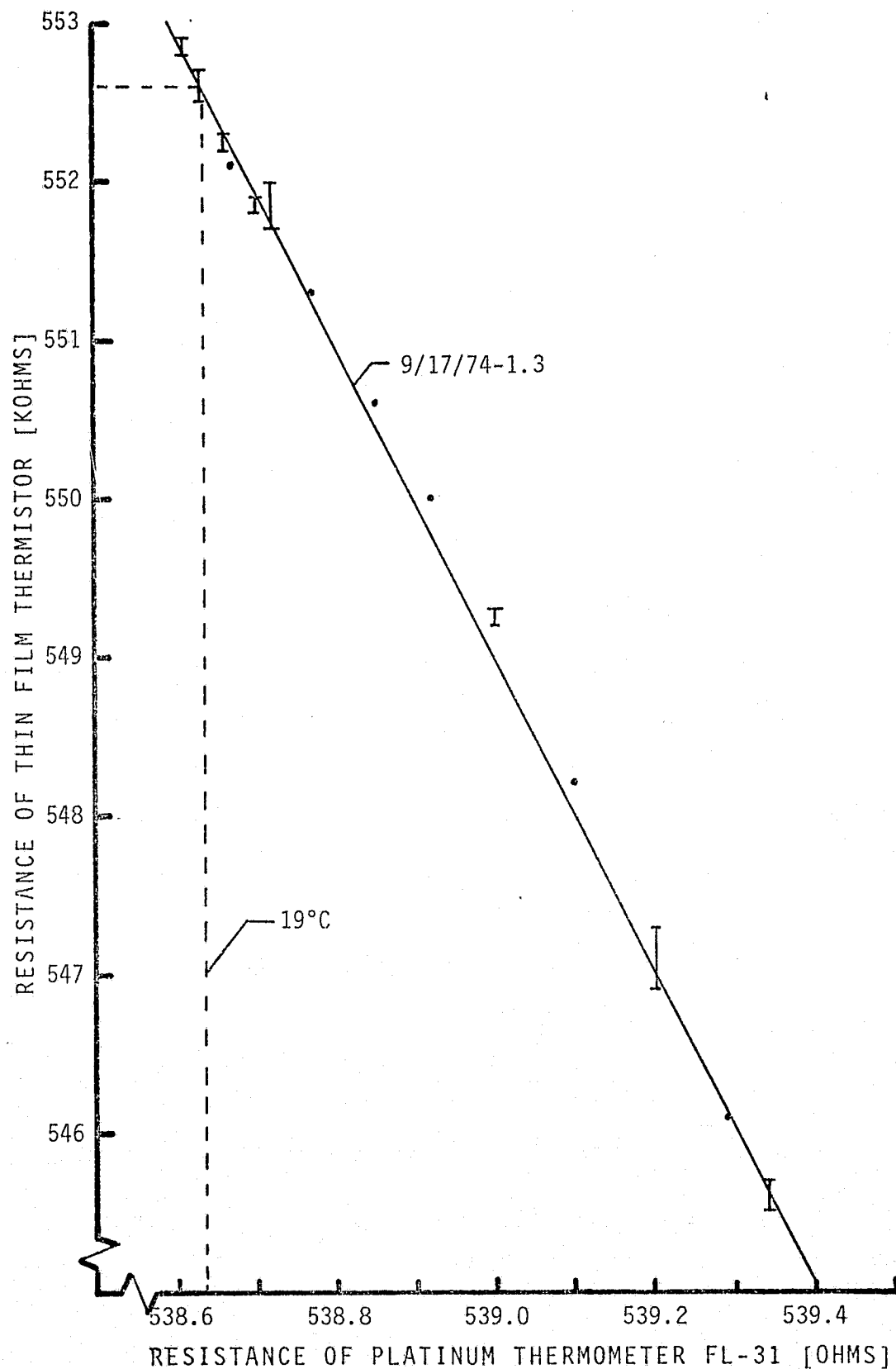


Figure 13. The resistance of thin film thermistor 9/17/74-1.3 as a function of the resistance of PRT FL-31.

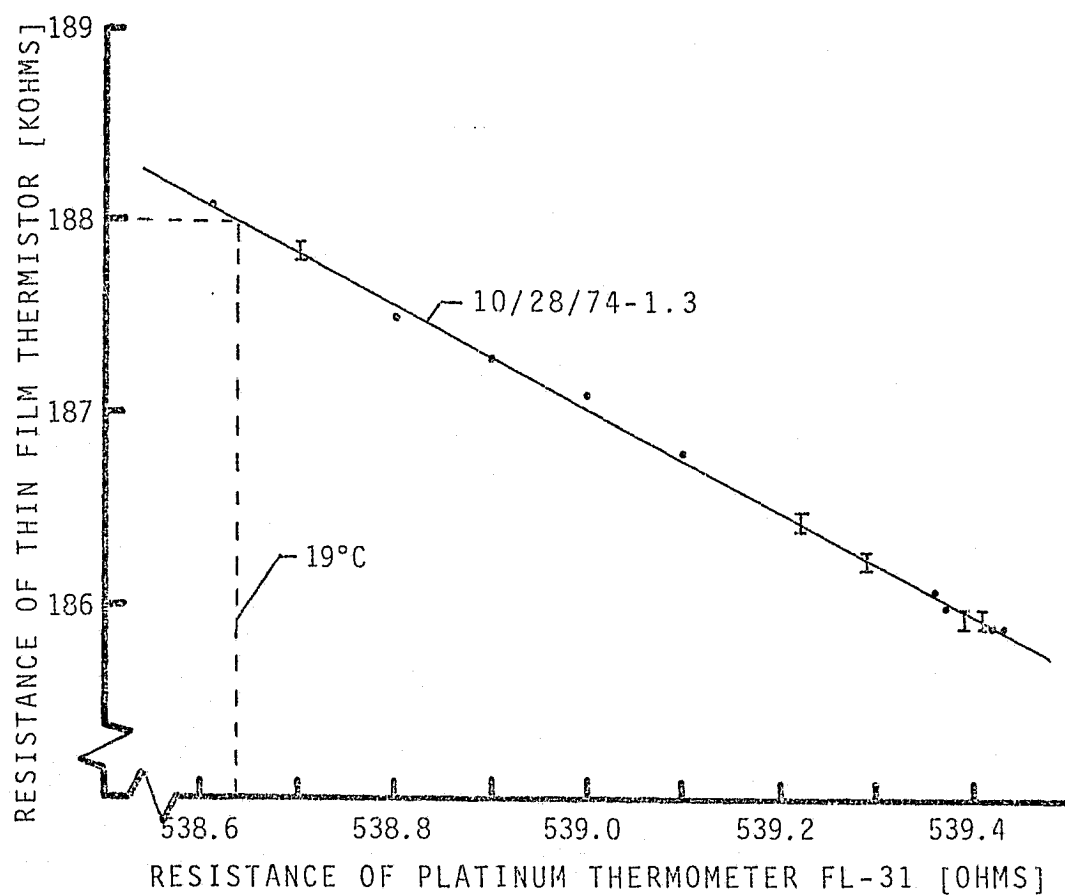


Figure 14. The resistance of thin film thermistor 10/28/74-1.3 as a function of the resistance of PRT FL-31.

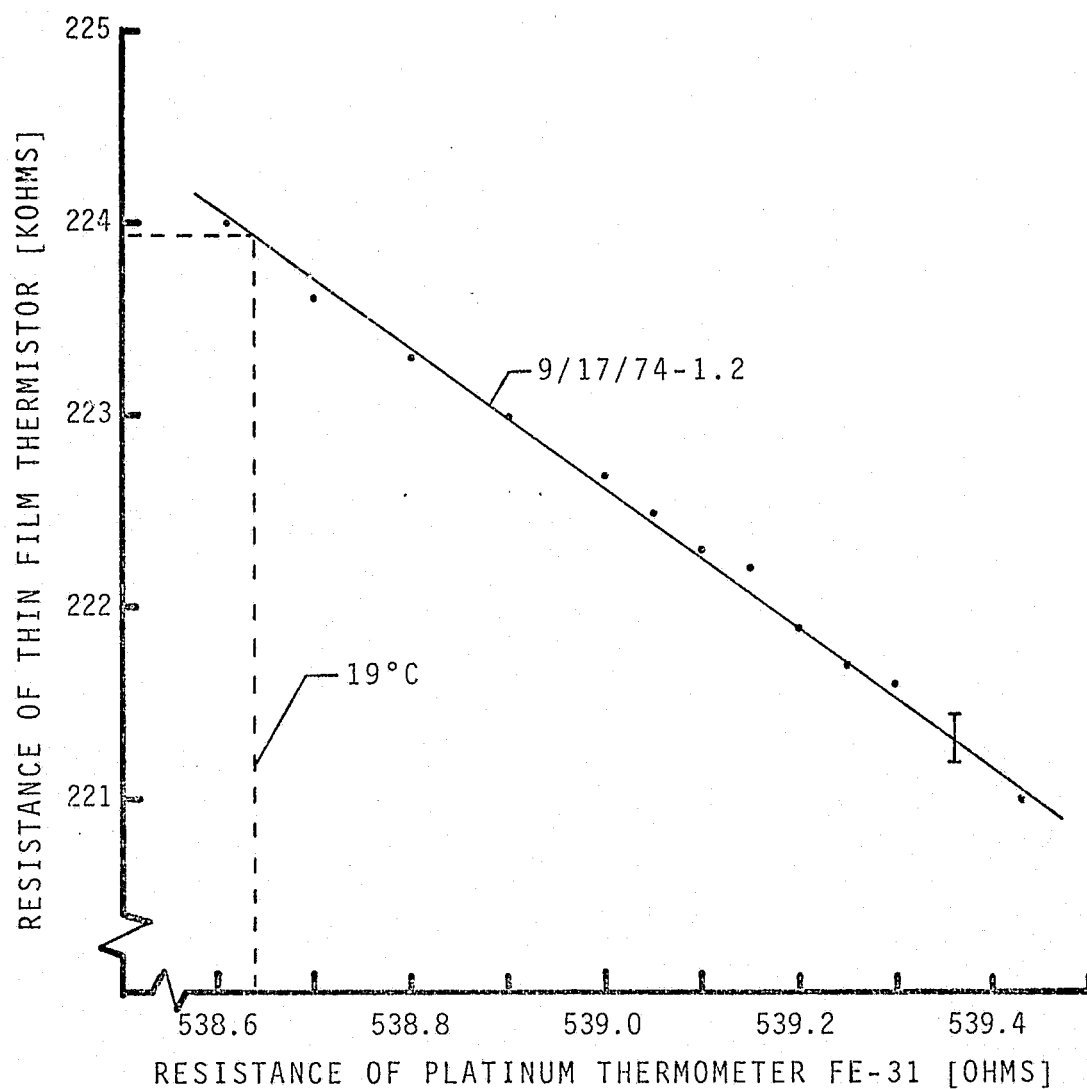


Figure 15. The resistance of thin film thermistor 9/17/74-1.2 as a function of the resistance of PRT FL-31.

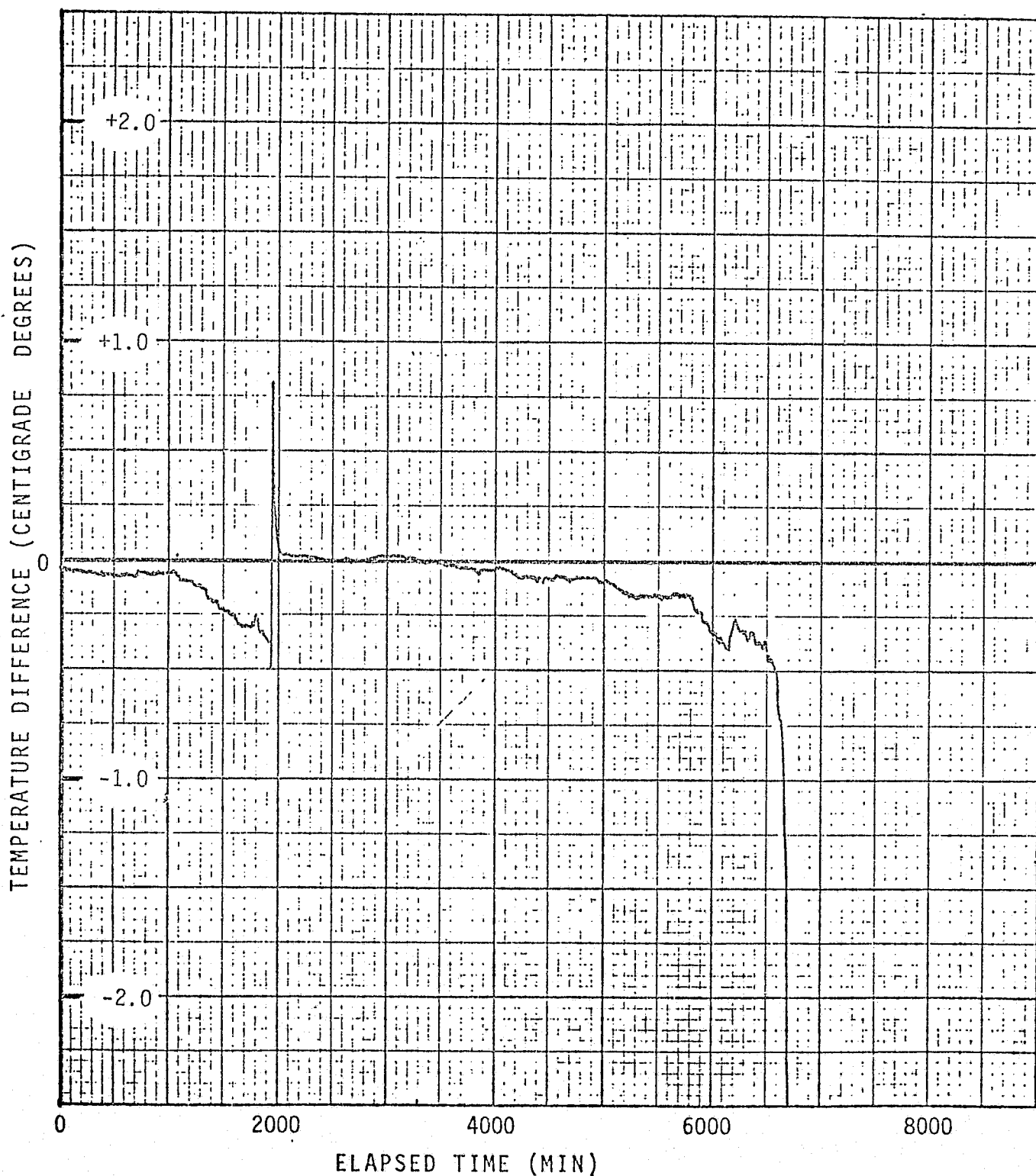


Figure 16. Plot of the difference in temperature between thin film sample 10/28/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 4.

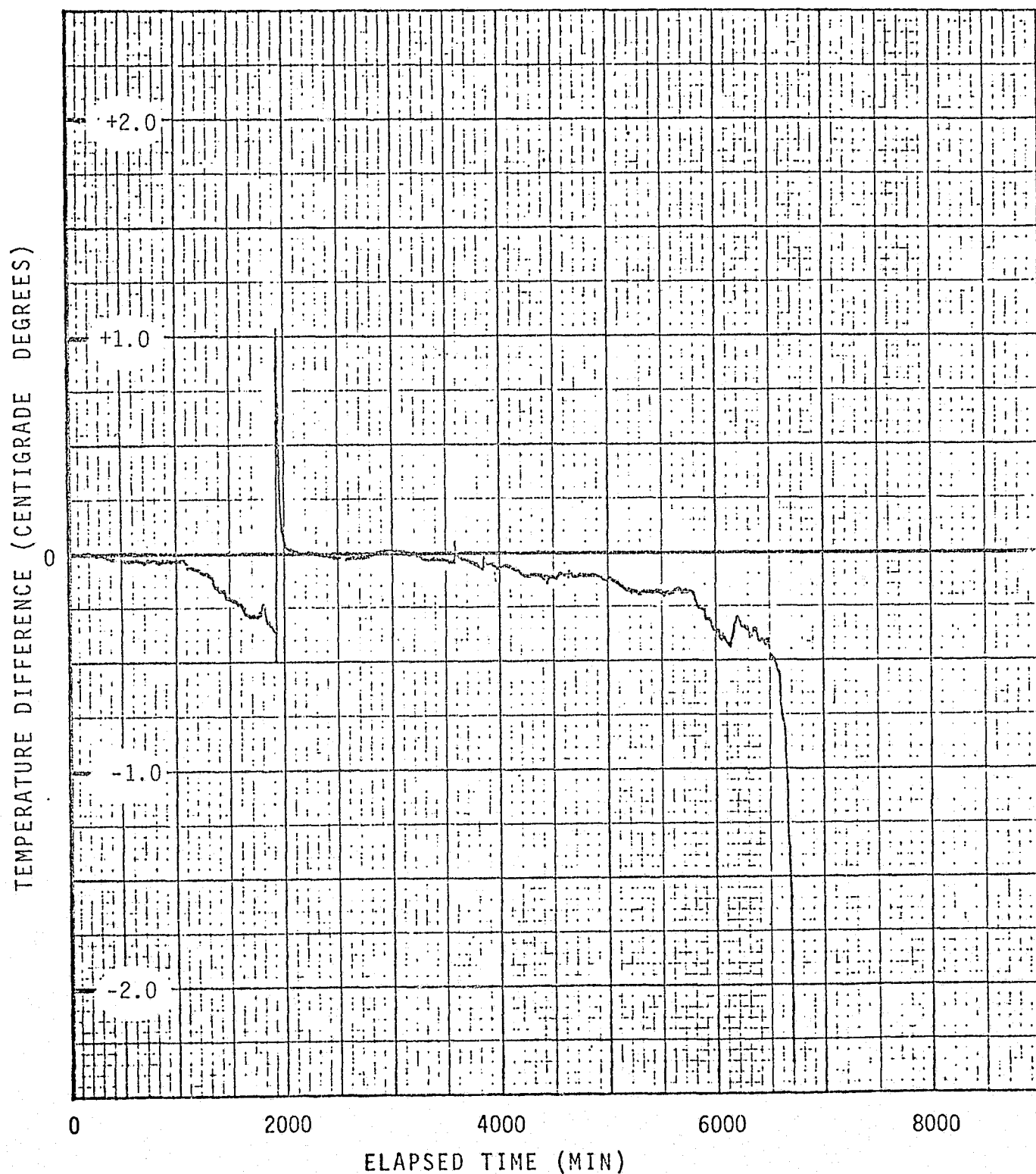


Figure 17. Plot of the difference in temperature between thin film sample 10/28/74-1.2 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 4.

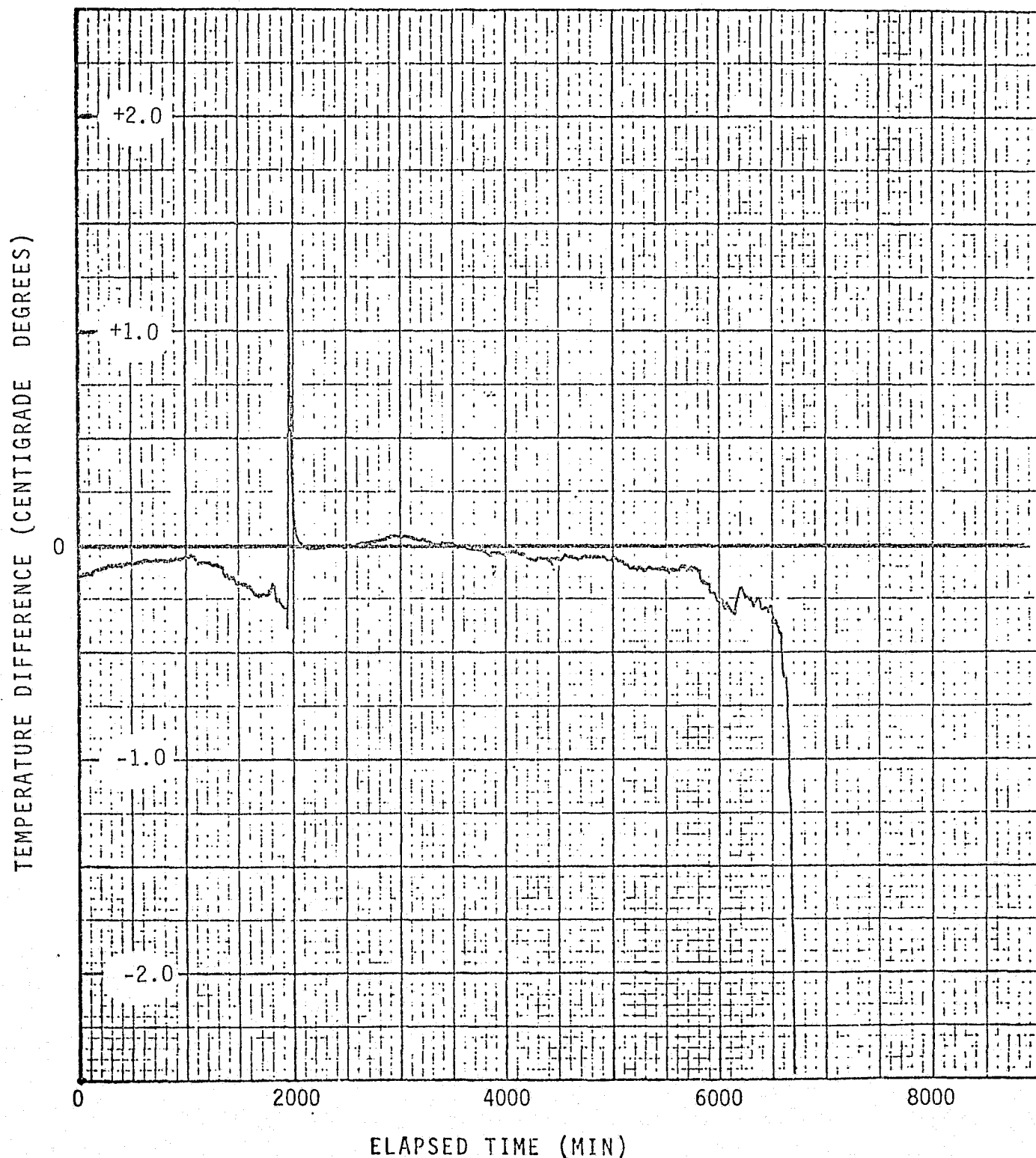


Figure 18. Plot of the difference in temperature between thin film sample 10/27/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 4.

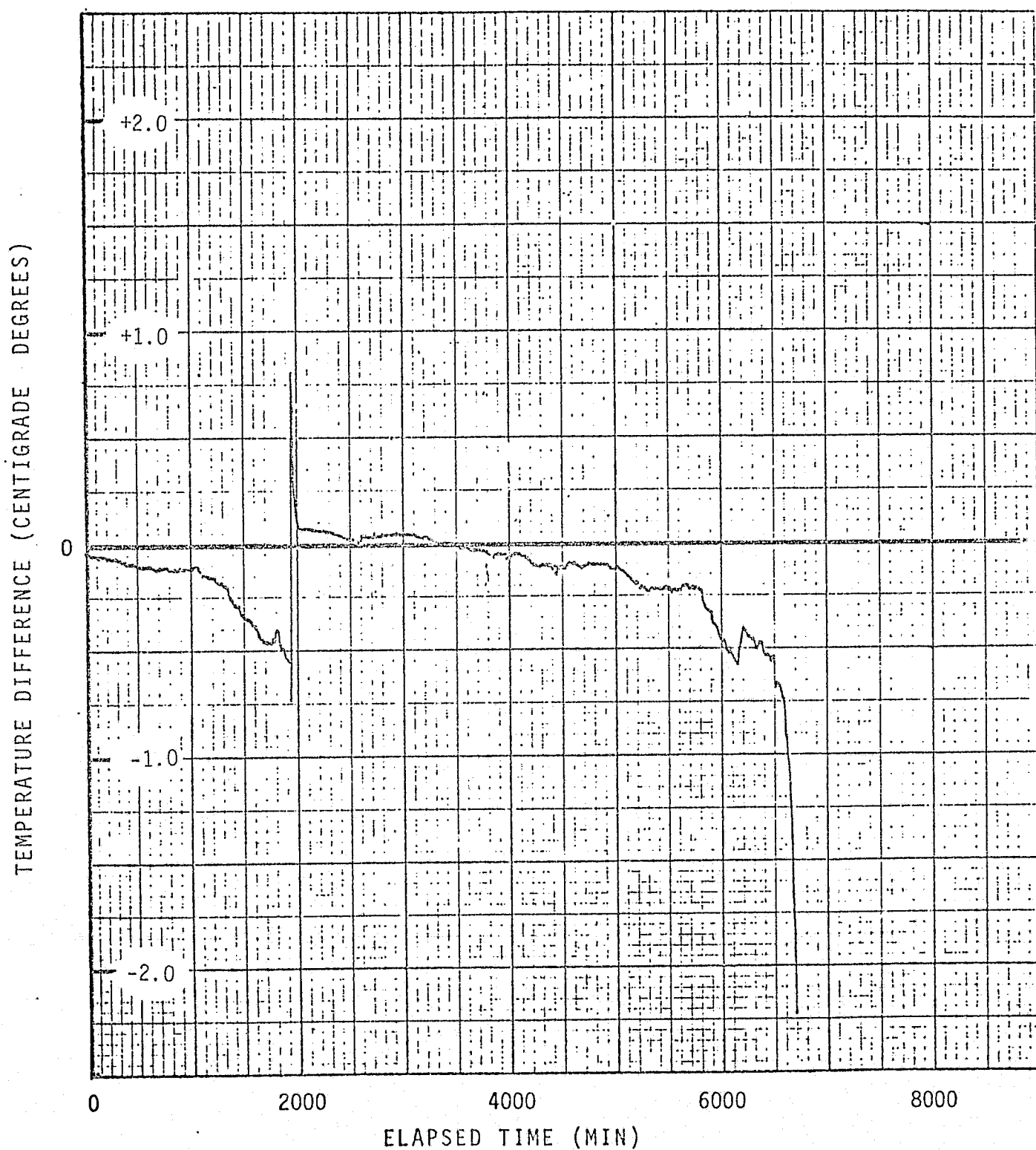


Figure 19. Plot of the difference in temperature between thin film sample 8 /25/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 4.

measurements it was omitted from these last four curves. (Four of the seven samples tested now yielded similar results.) No results are presented for the third group of samples since their characteristics continued to drift and any reasonable comparison was impossible.

SUMMARY

This research effort covered a period of five years. During that period the research furnished some degree of financial support to seven masters candidates and two doctoral candidates. In addition to these graduate students, a number of undergraduate students have benefited from the research either financially or through the use of the facilities. Three technical papers related to the research have been presented at technical meetings and published either in the proceedings of the meeting or in scientific journals. (These papers are listed at the end of this report.) At least one additional publication is anticipated at this time.

Sensors have been fabricated which have characteristics satisfactory for flight. Two difficulties which must be overcome before these devices are satisfactory for extensive use are the extensive time required for fabrication and the lack of uniformity in device characteristics. The first of these difficulties, fabrication time, could probably be solved using commercial facilities designed for high production rates. The second difficulty, uniformity, is characteristic of the entire semiconductor industry. Based on our work we believe that with careful control of the deposition process the majority of the devices fabricated will have satisfactory characteristics. With a proper selection procedure it should be

possible to select fabricated samples which possess satisfactory characteristics. In conclusion, if sufficient need exists to warrant mass production of the thin film thermistor it should be possible to produce satisfactory devices at a reasonable price.

PAPERS RESULTING FROM THIS RESEARCH

"A Thin Film Temperature Sensor" - W. D. McLennan, R. T. Ooten, D. S. Bynum, J. L. Palmer, K. N. Pendley, and C. R. Baxter

Presented at the 21st National Symposium of the American Vacuum Society; Anaheim, California; October 1974.

Published in J. Vac. Sci. Tech., Vol. 12, #1, pp. 71-3, Jan/Feb, 1975.

"Ovonic Switching in Tin Selenide Thin Films" - C. R. Baxter and W. D. McLennan

Presented at the 21st National Symposium of the American Vacuum Society, Anaheim, California; October 1974

Published in J. Vac. Sci. Tech., Vol. 12, #1, pp.110-3, Jan/Feb, 1975

"A Computer Controlled Procedure for Testing Memory Type Ovonic Switches" - C. R. Baxter, W. D. McLennan, A. R. Atkins, and B. W. Simpson

Presented at IEEE Southeastcon-75; Charlotte, North Carolina; April 1975 and published in the conference proceedings.

APPENDIX I

A DIGITAL CONTROLLER FOR THIN FILM DEPOSITION

A Dissertation

Presented to

the Faculty of the Graduate School

Tennessee Technological University

In Partial Fulfillment

of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

Engineering

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by

Allen Riley Atkins, II

August 1975

AN ABSTRACT OF A DISSERTATION

A DIGITAL CONTROLLER FOR THIN FILM DEPOSITION

Allen Riley Atkins, II

Doctor of Philosophy--Engineering

The need for a precise deposition rate controller is presented in a brief survey given in this dissertation. A digital controller for thin film deposition rate control was designed, fabricated, and tested. The hardware and software presented describes a system capable of thin film deposition rate control of better than .1 Å/sec. Other features the system includes are real time monitoring of the critical parameters, hardcopy output of these parameters, and a statistical analysis of the data taken during the deposition process. The results presented show that the control characteristics of the digital controller appear to exceed those of any other thin film deposition controller on the commercial market.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. William D. McLennan, chairman of the author's Graduate Advisory Committee, for his invaluable assistance and encouragement during this study. Appreciation is also extended to the Physical Electronics Research Group in the College of engineering and to Dr. S. G. Lele, Dr. A. E. Traver, Dr. J. T. Scardina, and Dr. Leland Long, members of the Graduate Advisory Committee, for their contribution and support during this study.

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The author is especially grateful to Mr. Charles Hardesty of NASA at Langley, Virginia, for the support given to this effort. Special appreciation is given to the author's wife and children for their support, sacrifices, and understanding during the author's educational efforts.

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LIST OF SYMBOLS

Symbol

α	(1-confidence level)
\AA	Angstrom units (10^{-10} m)
a_1	Adaptive Coefficient
a_2	Adaptive Coefficient
b_1	Adaptive Coefficient
b_2	Adaptive Coefficient
B2	Digital controller software input for velocity multiplier
CF	Controllability factor (Hz/sec)
C_K	Output of deposition process at k-th interval (Hz/sec)
e_K	Error signal to digital control law at k-th interval (Hz/sec)
e	2.7183
$f(x)$	Normal distribution for given mean and standard deviation
K_1	First rate data point in statistical analysis
K_2	Last rate data point in statistical analysis
M1	Proportionality constant to convert voltage--Hz/sec or voltage--Angstrom/sec (Hz/sec-volts, $\text{\AA}/\text{sec-volts}$)
M_K	Controller output at k-th interval
μ	Mean value of a distribution function
μ_u	Upper confidence limit for true mean value
μ_L	Lower confidence limit for true mean value
μ_R	Standard deviation of the rate variable
π	3.14159
n	Number of sample matrix points

Symbol

r_K	Desired rate of deposition (Hz/sec)
\bar{R}	Mean rate (Hz/sec)
R_i	Rate value at the i-th interval (Hz/sec)
R_F	Reproducibility factor (Hz/sec)
R_{IF}	Final rise setting for digital controller
R_{II}	Initial rise setting for digital controller
R_{12}	Mean rate between interval K_1 , K_2
S	Estimated standard deviation of a distribution about the mean
$S_{\bar{R}}$	Standard deviation about mean \bar{R}
$S_{\overline{SD}}$	Standard deviation about the mean \overline{SD}
\overline{SD}	Mean of a series of standard deviation values
σ	Standard deviation of a distribution about the mean
$t_{\alpha/2}$	Student t-distribution for confidence level of $\alpha/2$
T_R	Rise time
T_S	Soak time
V_i	Voltage measurement at the i-th interval
\bar{x}	Estimated mean of a normal distribution

Chapter 1

INTRODUCTION

In the area of thin film device fabrication, parameters such as rate of material deposition, film thickness, and substrate temperature influence the properties of the film device. Some researchers [1, 2] have concluded that the rate of deposition and the thickness of the film are probably the more important of the various parameters.

Precise control of the deposition parameters has become a must if the reproducibility of a thin film device with defined characteristics is to be expected. If valid data are to be gathered on the effects that these parameters have on the characteristics of the devices fabricated, then precise control is needed to insure that the variations in the characteristics can be correlated with the deposition parameters.

Electronic equipment that offers control of these two parameters has been available commercially for several years. Probably the first thickness measuring technique was described by Turner [3] and Butuzan [4]. It consisted of a bridge circuit to measure the resistance of the material as it was being deposited between two electrodes. Using this method, devices having desired resistances and thus thickness could readily be obtained.

Weissman and Hirsch [5] later developed a technique based on the torque produced by a moment arm being struck by evaporated particles to measure a signal which was proportional to the rate of deposition.

By integrating the "rate" signal, the thickness of the film could be obtained. The momentum associated with the particles of evaporant striking the surface at the end of a moment arm was measured and amplified to give a crude but novel method of obtaining the deposition rate.

In 1963, Brownell, McLennan, Ramey and White [6] introduced an automatic thin film vacuum deposition system. It consisted of a sub-miniature ionization gauge which was placed in the path of the evaporating material and measured the density of particles passing through the gauge, and thus, the rate of deposition. The signal from the ionization gauge, being proportional to the deposition rate, was used as a feedback signal for automatic rate control.

Concurrent with the introduction of the ionization gauge as a method for measuring and controlling deposition rate and film thickness, Lins and Oberg [7] developed the quartz-crystal monitoring system to accomplish the same function. Their system consisted of a thin quartz-crystal mounted such that one face of the crystal was exposed to the evaporation source. Connected in an oscillator circuit, the crystal's resonant frequency decreased as the thickness of the material deposited on the exposed face increased. By subtracting this crystal frequency from that of an oscillator of fixed frequency, a variable frequency signal directly proportional to the thickness of the film was realized. Compactness, accuracy, and response speed made the quartz-crystal monitor the state of the art method for monitoring the rate and thickness parameters. Lawson [8], using a quartz-crystal monitoring system, was able to measure film thickness during deposition to an accuracy of one percent.

Even though the quartz-crystal monitoring system offered many advantages over other methods of monitoring and control, it too had some disadvantages [9]. The primary problem, illustrated in Fig. 1.1, was a sudden frequency shift of the quartz-crystal during deposition. At points A and B, one can see that the frequency output from the crystal took an abrupt change and, in both cases, generated an abrupt increased rate indication which in turn caused an abrupt change in the controlling voltage to the electron gun.

The cause for these frequency shifts has been attributed to combinations of thermal, mechanical and/or electrical shock. Since the thermal effects appear to influence the frequency stability more than the other effects, various techniques have been suggested to curtail this effect. Thermally shielding the outer casing of the sensor was a possible solution suggested by Riegert [10] to ease the thermal effects. Other suggestions which have been made include mounting the crystal on blocks with high thermal inertia, i.e., heat sinking, water cooling the sensor walls or placing optical baffles to cut down on radiation heating. Even with the use of thermal shielding and the other techniques, the problem of unexpected frequency shifts still exists.

Until the introduction of the computer, an accurate rate controller capable of handling these frequency shifts appeared unrealizable. In 1972, Effron, Farrow, and Thitcomb [11] of IBM produced a system consisting of a vacuum deposition unit controlled by a large computer. With their system a reproducible copper-tin metallic film could be achieved, along with the added capability of real time data monitoring, storage, retrieval, and computation. Although statistical information indicated how well the computer controlled both the thickness and the

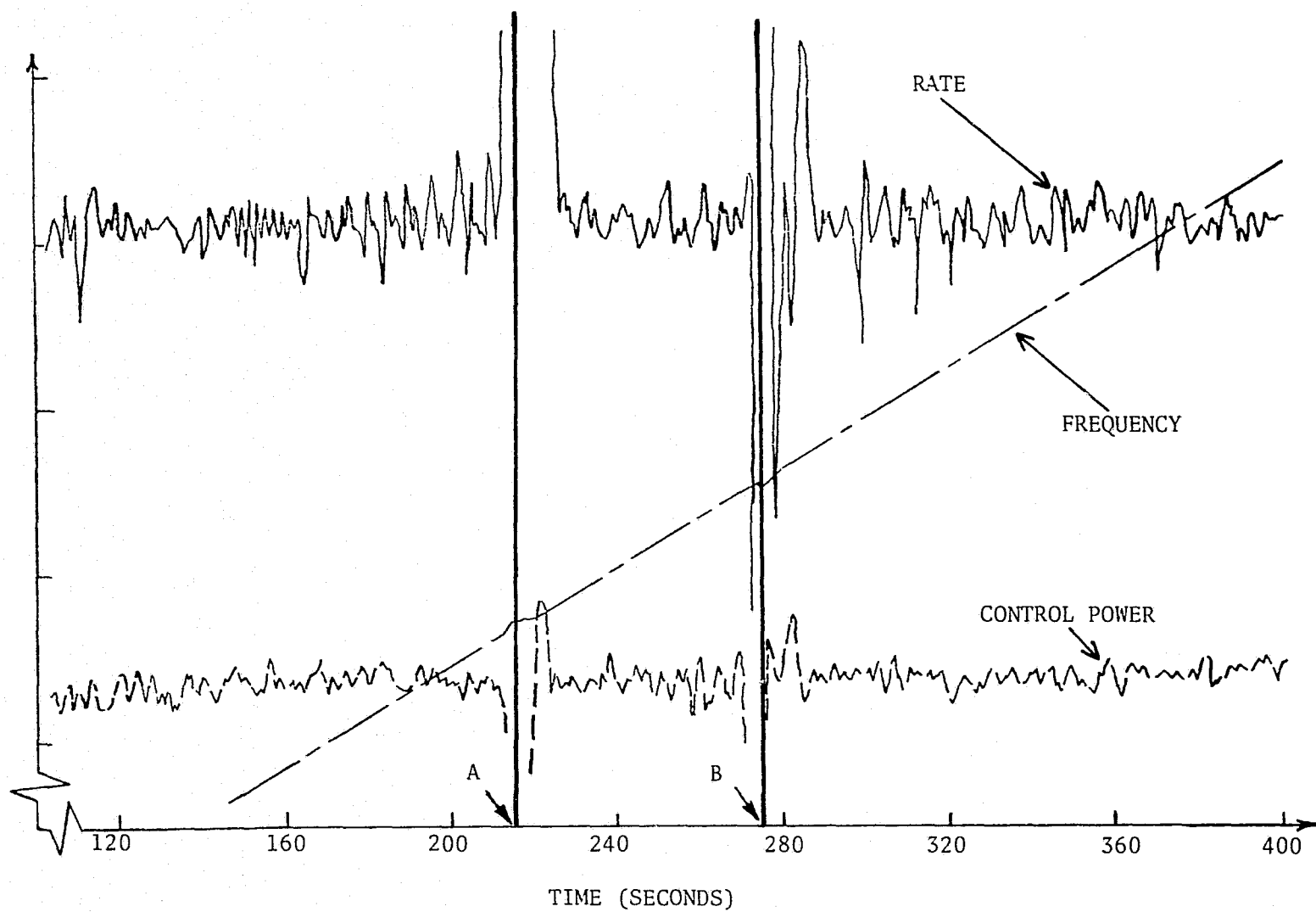


Figure 1.1. Analog Response to Crystal Snap

average deposition rate, there was no indication as to the uniformity of the rate control (i.e., how much standard deviation from the average could be expected). Also, no effort was made to use the system for controlling the deposition of materials other than metals. This is important since semiconducting materials are far more sensitive to variation in the deposition parameters. Techniques utilizing the computer to alleviate the unexpected frequency shift associated with the crystal monitor proved to greatly enhance the monitoring technique. Therefore, the possibility of using the computer to monitor and control thin film deposition parameters appeared to be feasible.

At the same time the IBM system was being developed, Centner and Wilson [12] investigated the possibility, from a theoretical and economical standpoint, of using a digital processor (mini-computer) to achieve the same results. They suggested the primary advantage of using the digital processor as compared to either a large machine or an analog unit was the cost factor. The cost advantage that most digital processors have in comparison to digital machines is obvious, but their cost advantage over an analog deposition controller is not readily evident. The cost of an analog control unit including sensor heads and the accessories necessary to control the rate of deposition, film thickness, and shutter operations can be purchased at a cost equal to or less than the cost of a digital processor and the associated hardware necessary to accomplish the equivalent function. If, however, additional hardware were added to the analog system to allow monitoring, data storage, and retrieval, it would cause the analog system cost to far exceed the equivalent computer system.

Centner and Wilson concluded that another possible advantage the digital processor system offered was that the system would be much more flexible than an analog system. Not only would monitoring and control be possible, but other functions such as data manipulation, statistical analysis, mathematical problems, and other services normally performed by a computing system would be available by changing only the software of the machine. Thus, a greater degree of flexibility could be achieved by using the digital processor to control and monitor the deposition parameters such as deposition rate and film thickness. Also, this approach appears to have advantages over an analog control device if the control achieved by the digital processing system equals or exceeds the control of the analog system.

Figure 1.2 shows a model of the vacuum deposition unit interfaced with an analog control unit, presently in use at Tennessee Technological University. The system shown achieves deposition rate control by mixing the signal from the quartz-crystal sensor with an adjustable frequency oscillator to obtain a low frequency signal directly proportional to the thickness of the material being deposited. This signal is converted to a DC voltage level which can be compared to a voltage level representing the desired film thickness. The difference signal can be used to control the termination of the deposition. By differentiating the DC voltage level with respect to time, a signal proportional to the deposition rate can be obtained and compared to a desired deposition rate. The difference between the two rate signals is then used to control a SCR power controller which supplies power to an electron gun. The electron gun, in turn, supplies energy to the evaporant, causing it to evaporate.

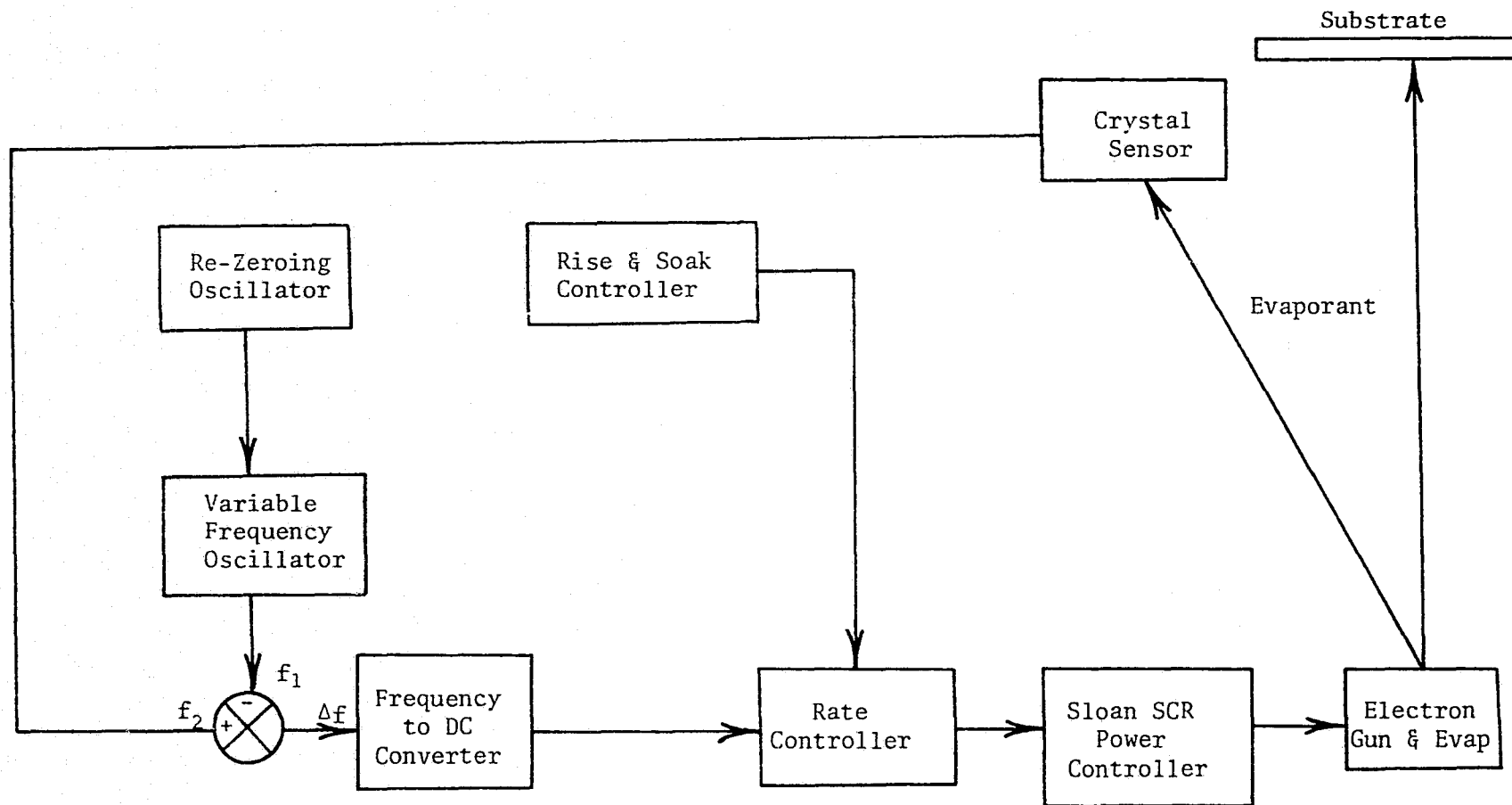


Figure 1.2. Analog Deposition Processor

Thus, a complete feedback system using analog components controls the deposition rate and film thickness.

This dissertation establishes the design criteria for a digital system which will replace parts of the analog system. The hardware and software requirements to perform the task are also defined. Finally, a series of digitally controlled depositions have been made for a comparative analysis with the analog controller. The results of the analysis will illustrate that the digital controller offers many advantages over the analog controller.

Chapter 2

SYSTEM DESCRIPTION

This chapter contains a discussion of the hardware used to initially monitor and ultimately control the deposition process. Each major system, the Analog, the Analog/Digital, and the Digital Control Unit depicted within the block diagram of Fig. 2.1 will be discussed. Only the Analog System existed prior to the undertaking of this research effort. The remaining major systems were designed and integrated to develop the monitoring and deposition controlling system to be discussed. The portion of the figure encompassed by the dashed line is used to monitor the parameters which are set by the analog controller while the entire figure illustrated all components needed to both monitor the deposition and to digitally control the process.

ANALOG SYSTEM

The analog system is illustrated in Fig. 2.2. The components are the SCR Power Controller, Power Transformer, Vacuum Chamber, Electron Gun, Material Crucible, Crystal Detector, and the Analog Rate Controller. Beginning with the SCR Power Controller and following the path of the process, the components of the closed loop control system can be defined. The SCR Power Controller acts as a regulator controlling the power signal. That is, the conductive or "on" portion of the power cycle is controlled by the input signal to the SCR Power Controller.

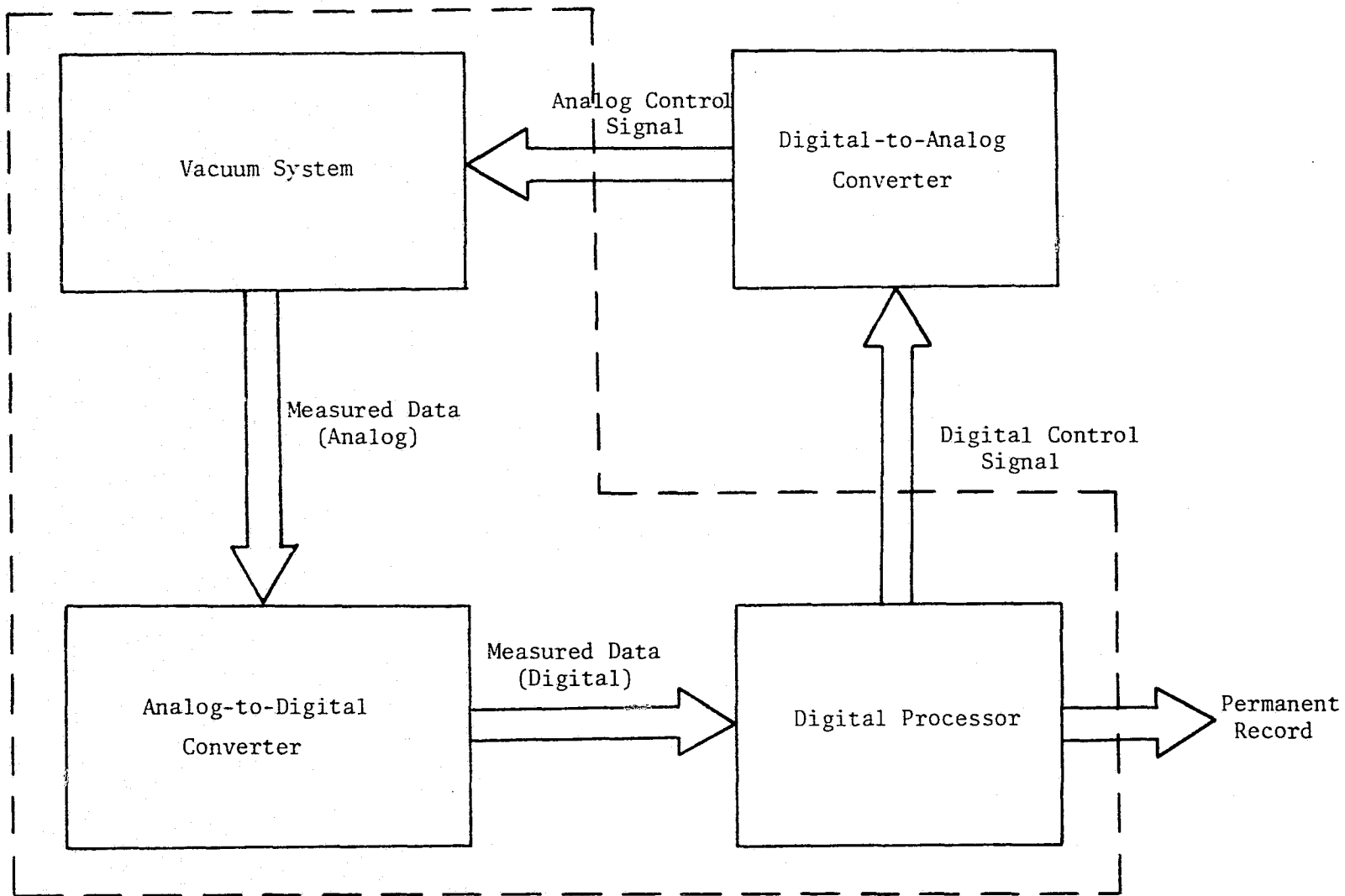


Figure 2.1. Deposition and Monitoring System

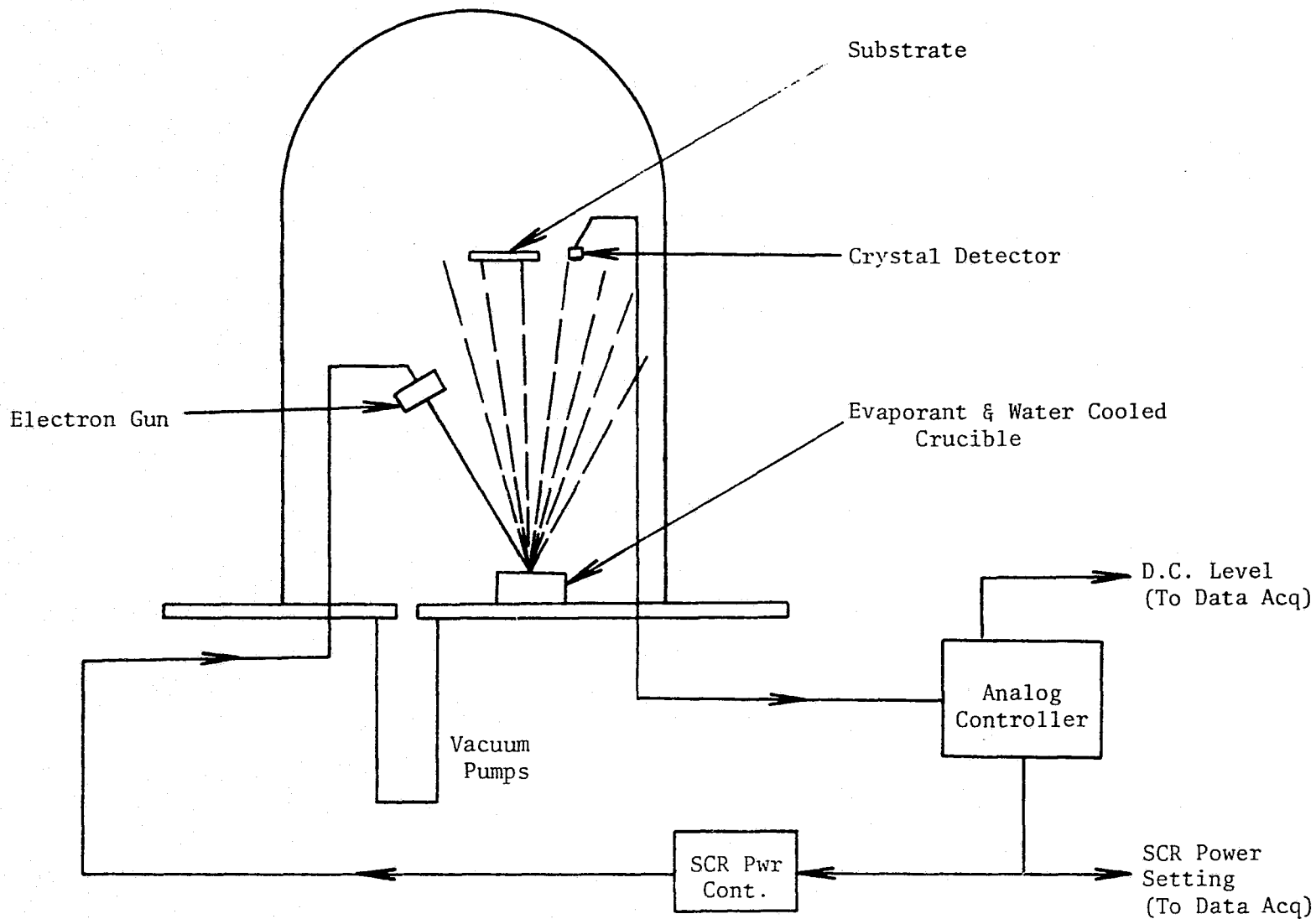


Figure 2.2. Vacuum System

Figure 2.3 illustrates the SCR Power Controller and associated circuitry. The power transformer transforms the 208 volts (AC primary voltage) to an 11 Kilovolt DC output which is superimposed on the AC signal applied to the filament of the electron gun in the vacuum chamber.

The next subsystem to consider is the electron gun. It is capable of delivering up to 6 Kilowatts of power to a water cooled crucible filled with the evaporant. The power supplied to the crucible results when the electrons are emitted from the tungsten filament and accelerated through the 11 Kilovolt potential difference between the filament and the grounded hearth. The gain in kinetic energy is transformed to thermal energy when the electrons strike the deposition material in the crucible. Utilizing the electrostatic fields generated by the high electric potential and the circular geometry of the electron gun, the stream of electrons boiled off the filament is focused to a narrow beam. Once through the electrostatic lens, the beam of electrons experiences very little diffusion due to collisions with other particles within the vacuum chamber. Consequently, the mean free path of the electrons is long. This means the beam power is concentrated within a small region of the crucible.

The high velocity electrons impinging on the evaporant contained in the water cooled crucible are illustrated in Fig. 2.2. The evaporant molecules gain enough energy from the beam to escape the internal bonding forces and evaporate. Most of the evaporant molecules travel in a straight line until they strike a "cool" surface where adhesion with the surface occurs. Thus, adhesion can take place on any surface that is in direct line of sight from the surface of the material being evaporated. Two such surfaces are the substrate on which the thin

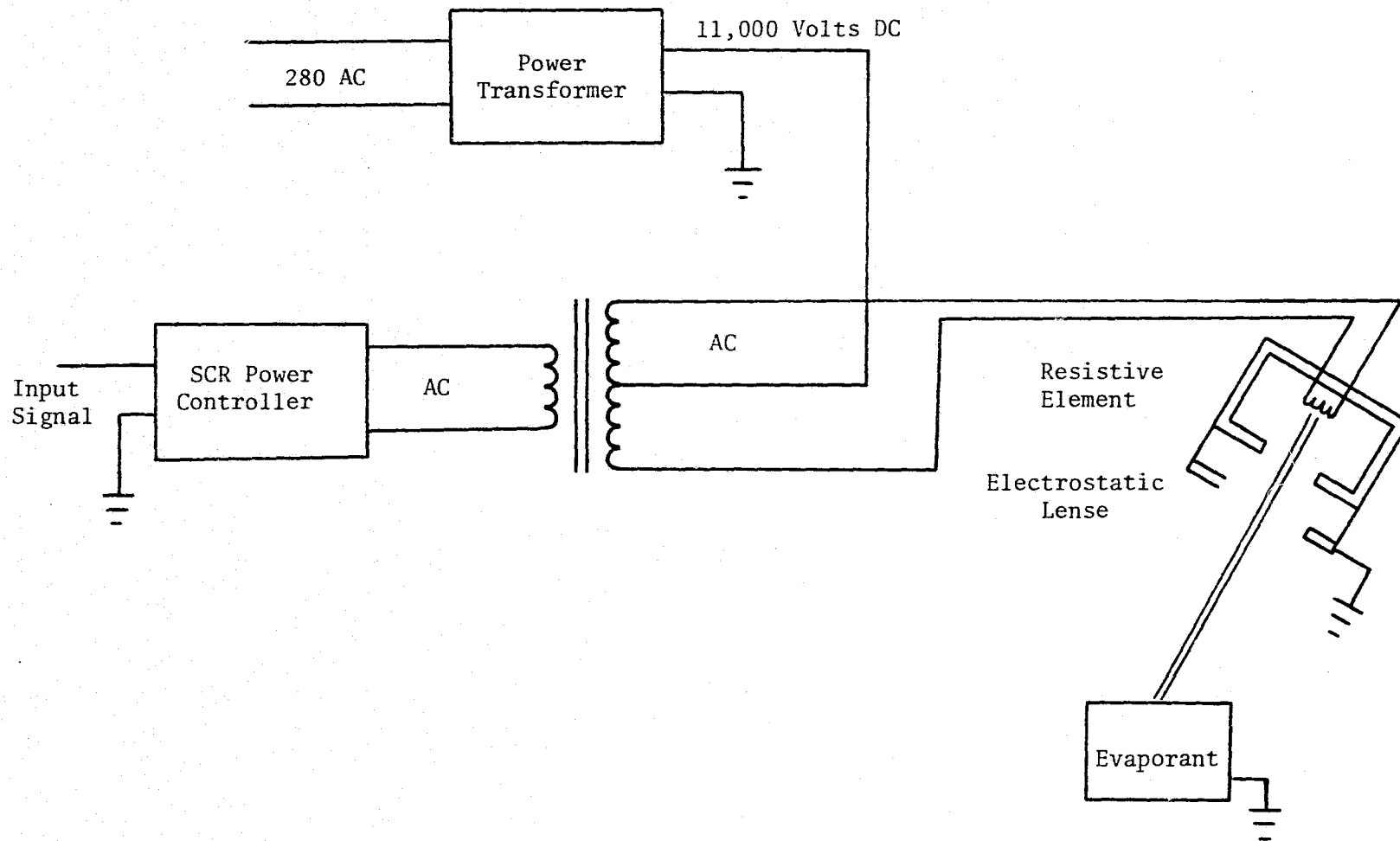


Figure 2.3. Electron Gun Control Diagram

film device is being fabricated and the face of the quartz-crystal monitor.

This evaporation process can be shown to be influenced by two prime factors. The first and probably the most influential is the surrounding, or background pressure, within the vacuum chamber. The higher the background pressure the more energy required to produce a given deposition rate since the mean free path of a molecule is proportional to the background pressure. The second factor that can be shown to have an influence on the evaporation process is the conductive heat transfer coefficient of the evaporant. A material that has a high conductivity coefficient, such as silver, will transfer a large amount of received energy through the material and into the water cooled crucible; while a material with a lower conductivity coefficient, such as the semiconductor material, tin selenide, will not transfer as much of the received energy to the crucible and thus less energy is needed to achieve a given deposition rate.

As indicated, two surfaces which become coated with the evaporant during the deposition process are the substrate and the crystal detector. The crystal detector has the role of a transducer. It transforms the presence of a given mass deposited upon the face of a quartz-crystal into an electrical signal which is readily detectable and satisfactory for processing. As the material is deposited upon the crystal, the resonant frequency of the crystal decreases. Thus, a measurable signal which is proportional to the material deposited is obtained.

The crystal utilized within the system has a resonant frequency near 5 MHz. By mixing this signal with a 5 MHz reference signal, a low frequency difference signal can be obtained which is proportional to

the thickness of the mass on the detector face. Figure 2.1 illustrates the next step in the control process which involves the conversion of the frequency signal into a DC signal. In completing the deposition process loop, the DC signal is coupled through a differentiator to obtain a signal proportional to the rate of change of the DC signal. Both signals, the DC voltage corresponding to the thickness indication and the rate of change of the DC level, are coupled to a pair of analog meters to give a real time indication of their variation during the deposition process. The deposition rate signal is compared with a reference signal and the difference is used to drive the SCR Power Controller in order to obtain the desired deposition rate.

As indicated in Chapter 1, there are some disadvantages associated with the analog rate controller. These include crystal snap, noisy differentiation of the DC signal, long settling time, high rate overshoots, inaccurate meter indications, and lack of permanent records of the deposition parameters. The limitation on the maximum time the system allocates to the rise time and the soak time is another disadvantage. The rise time refers to the time required to linearly raise the SCR Power Controller's output to a given setting while the soak time refers to the time this setting is sustained by the system. This limitation becomes an important factor for some materials such as tin selenide which requires a long rise time and platinum which requires a long soak time for outgassing.

This section has described the analog deposition system. Limitations associated with various subsystems have been discussed along with the effects the limitations can have on the deposition process.

This presentation will serve as a basis for discussing the analog-digital system.

ANALOG-DIGITAL SYSTEMS

This section of the chapter will discuss the hardware involved in converting the DC signal from the frequency to DC converter into a digital signal which can be sensed by the Digital Control Unit (DCU) and the subsequent generation of a control signal to be used for controlling the SCR power supply. The first half of this process requires an analog-to-digital (A/D) signal conversion and is referred to as the monitoring process. The second half requires both a digital-to-analog (D/A) and an A/D signal conversion and is referred to as the controlling process.

Since the A/D converter is required in both the monitoring and controlling processes, it will be discussed first. To perform this conversion, a Hewlett Packard Model 2012A Data Acquisition Unit was used in conjunction with control signals from the DCU. As illustrated in Fig. 2.4, the data acquisition unit is composed of two distinct units, a crossbar scanner and a digital multi-meter (DMM). The 600 channel crossbar scanner is used to select the desired analog data signal to be converted. Other signals, including the DC signal from the vacuum system, are available at the crossbar scanner and can be measured by the system. When controlled by the DCU, the crossbar scanner can be commanded to step through data channels in any desired sequence.

The chosen signal is routed to the DMM where it is converted to a digital signal that can be displayed on the front panel and is simultaneously routed to the DCU. The DMM is capable of interpreting

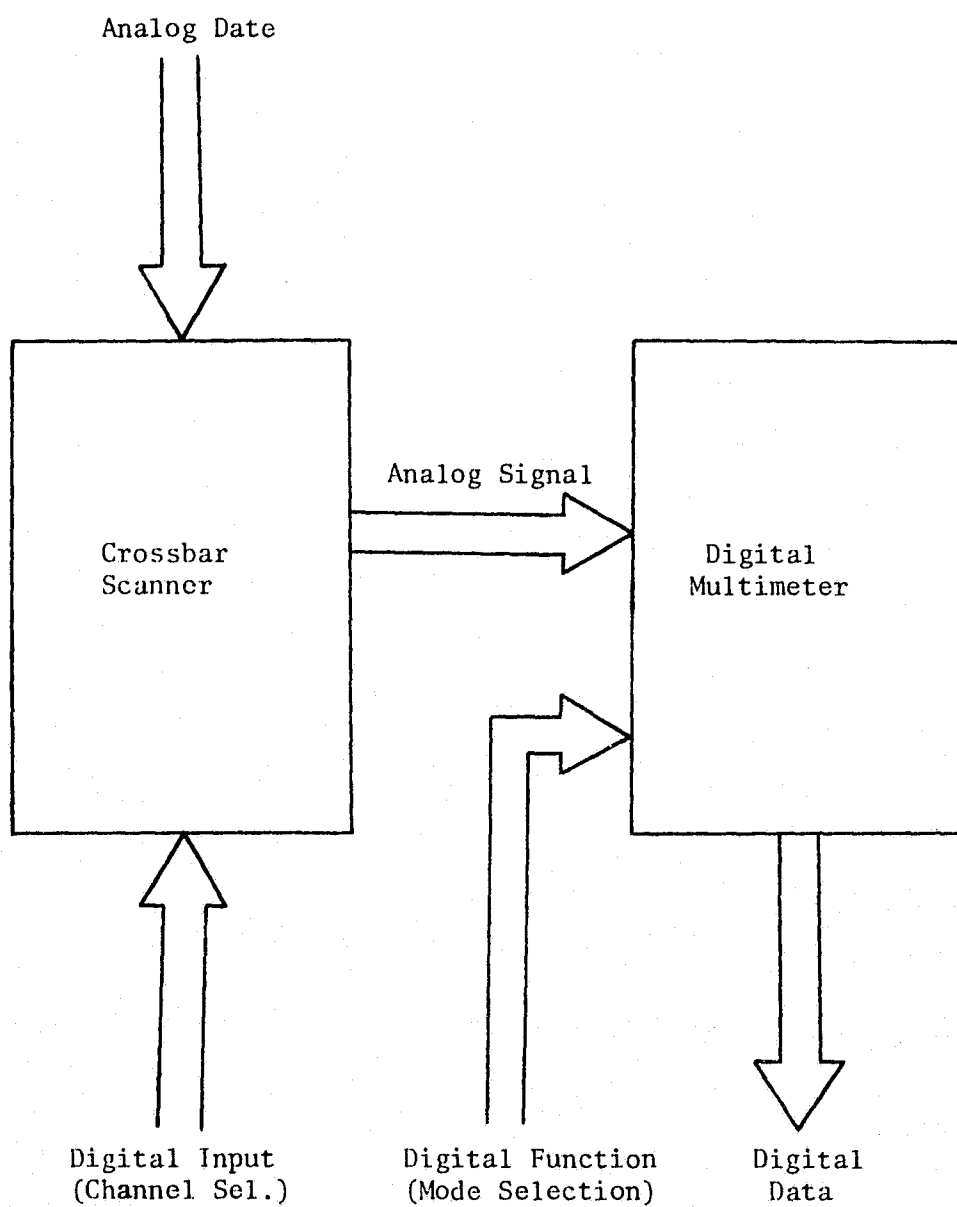


Figure 2.4. Analog-to-Digital Converter

the analog signal as a voltage, a resistance, or a frequency signal depending on the command from the DCU.

One might question the conversion of the crystal signal to a DC signal when the DMM has the capability of frequency measurements. The primary concern is speed. To convert an analog sinusoidal signal to a digital signal, the DMM requires a steady state analog signal for a one second measurement interval in order to reduce the measurement error. Two problems are associated with direct frequency measurement, the frequency changes during the measuring interval and the excessive time required for a measurement. Trying to control a deposition process at a constant rate of 10 Hz/sec frequency shift would generate an invalid digital signal. With reference to the second problem, the measurement interval, the digital control process requires an input signal every second. However, a full second is required for the measurement and additional time is required to transfer the data and commands.

To circumvent the problems associated with the frequency measurement techniques, the linear conversion of the frequency signal to a DC signal offers a plausible solution. The DMM is capable of taking a voltage measurement in approximately 50 milliseconds. Since the signal is normally varying less than 15 Hz/sec, the voltage measurement is sufficiently fast to allow errors due to signal variation during measurement to be neglected.

To make a measurement, a digital command from the DCU to the crossbar scanner chooses the proper channels to be measured. The selected analog signal is routed to the DMM where a command from the DCU directs the corresponding function, voltage in this case, to be measured and processed in digital output terms for transfer to the display unit

and the DCU. Once the process has been completed, the DCU receives a signal from the DMM indicating that the analog signal has been processed and is ready for transfer.

A digital signal from the DMM is received by the DCU in both the monitoring and controlling phases. In the controlling phase, the DCU operates on the digital signal to determine an output signal needed to drive the process to the desired value.

The next subsystem to consider is the digital-to-analog converter, illustrated in Fig. 2.5, which takes the digital control output signal from the DCU and converts it to the analog signal used to drive the SCR power controller. The need for a 0 to -9 volt input signal to the SCR power controller resulted in the selection of a standard digital-to-analog (D/A) converter having an output level of 10 volts. The D/A chosen will convert a 12 digit binary number into an analog voltage proportional to the binary number. Thus, a 10 volt full-scale output is capable of being divided into 2^{12} or 2096 increments. This allows control of the analog signal to within 2.5 millivolt. Coupled to the output of the D/A is an operational amplifier with a negative unity gain factor which converts the positive output of the D/A to a negative signal compatible with the SCR power controller.

DIGITAL CONTROL UNIT

The heart of both the monitoring and controlling phases is the DCU. Designed around a PDP 11/20 digital processor, the DCU is coupled to peripheral components, Fig. 2.6, through appropriately designed interfacing. Each component can be polled individually by the processor and

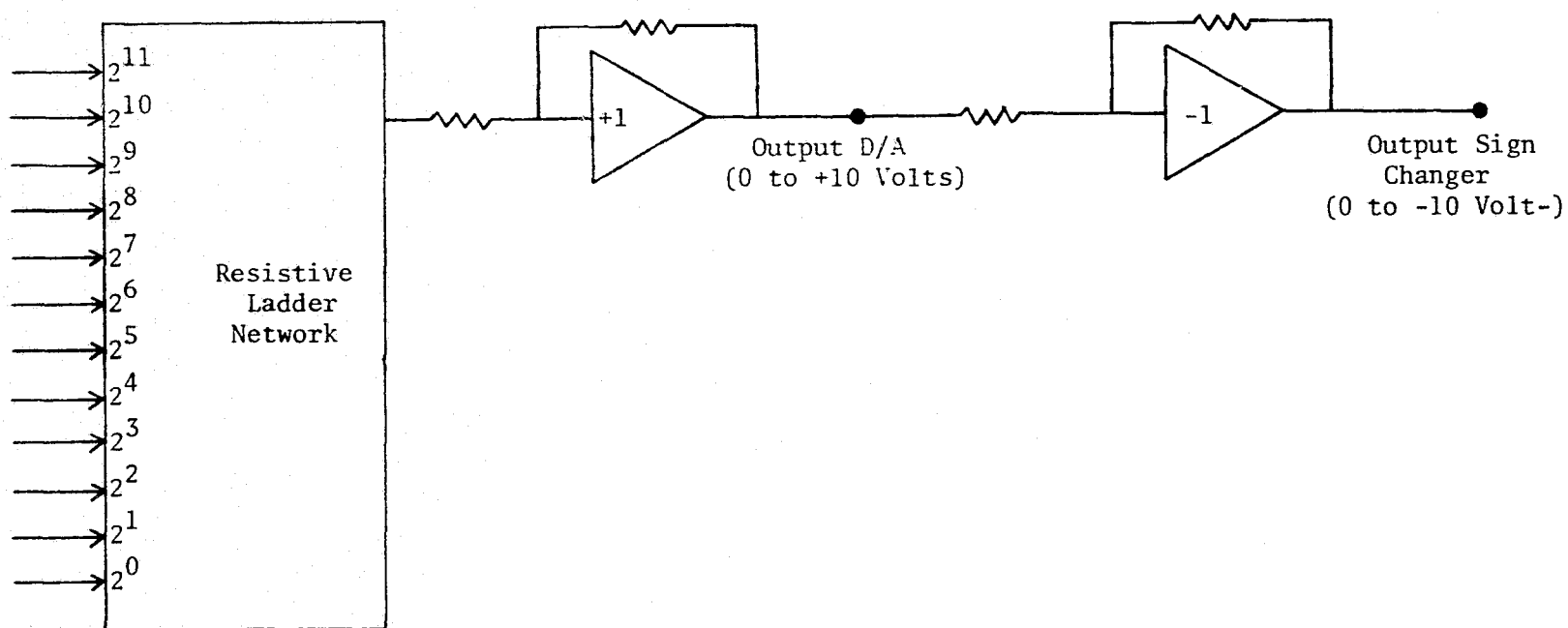


Figure 2.5. Digital-to-Analog Converter

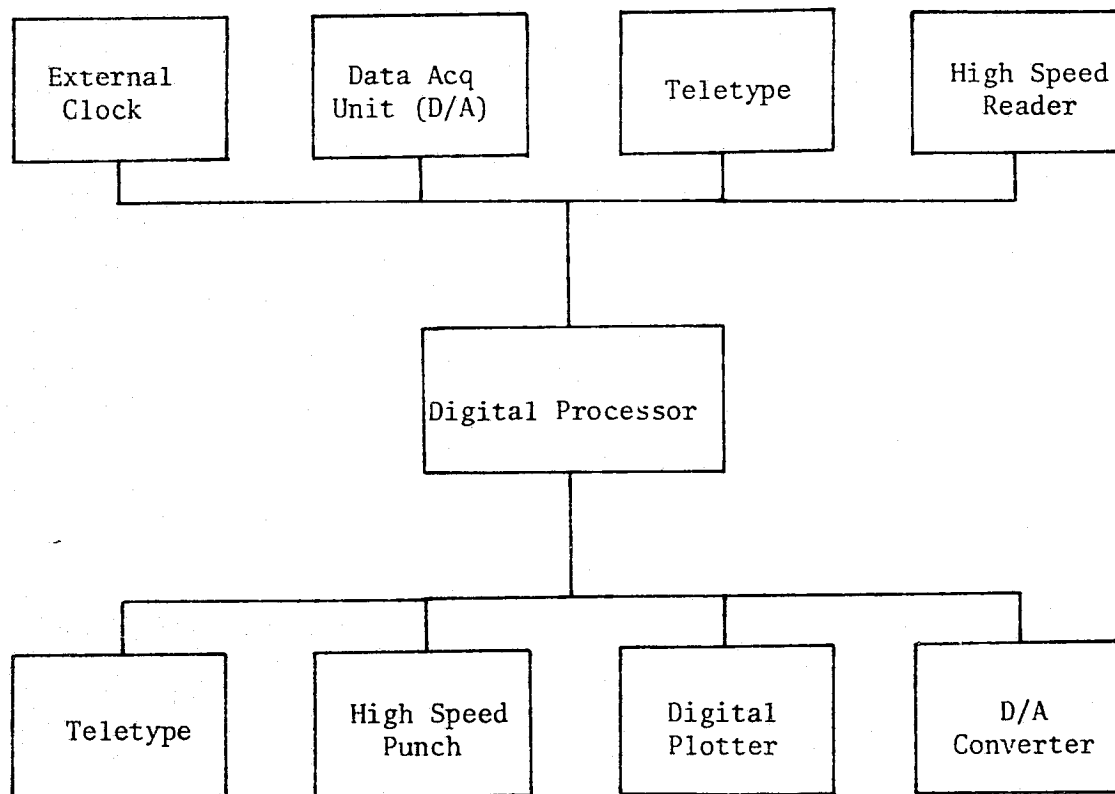


Figure 2.6. Digital Control Unit

data either transferred from the processor or from the peripheral device to the processor.

Probably the most important peripheral item is the teletype, because of its capability to converse with the processor in a conversational manner familiar to both the user and the processor. The next most important subsystem is the High Speed Reader/Punch (HSR/P). This unit makes it possible for pre-punched data tapes to be read by the processor. The processor can also use the HSR/P to punch data stored in its memory onto a paper tape for further analysis. In a similar manner the processor uses the digital plotter to plot the rate and control signal data taken during the monitoring and controlling phases.

The next peripheral device considered is the general purpose interface (the DR11-A) which allows various digital data to be interfaced to the processor. The DR11-A is the interface between the processor and the real world in both the monitoring and controlling phase of the processing. As illustrated in Fig. 2.7, connected to the DR11-A, via a 4 channel multiplexer, is various peripheral hardware including the D/A, A/D, DMM, crossbar scanner, and an external clock.

The external clock is used to indicate to the processor, at uniform discrete time segments, when it is time to perform certain functions. The primary purpose of the external pulse clock is to allow the processor to take frequency data at precisely one second intervals.

The "work horse" of the digital control unit is the PDP 11/20 digital processor. A high speed processor with an average cycle time of 1 microsecond, the processor is capable of acting as a "stand alone" unit for independent problem solving. It can also be used in conjunction

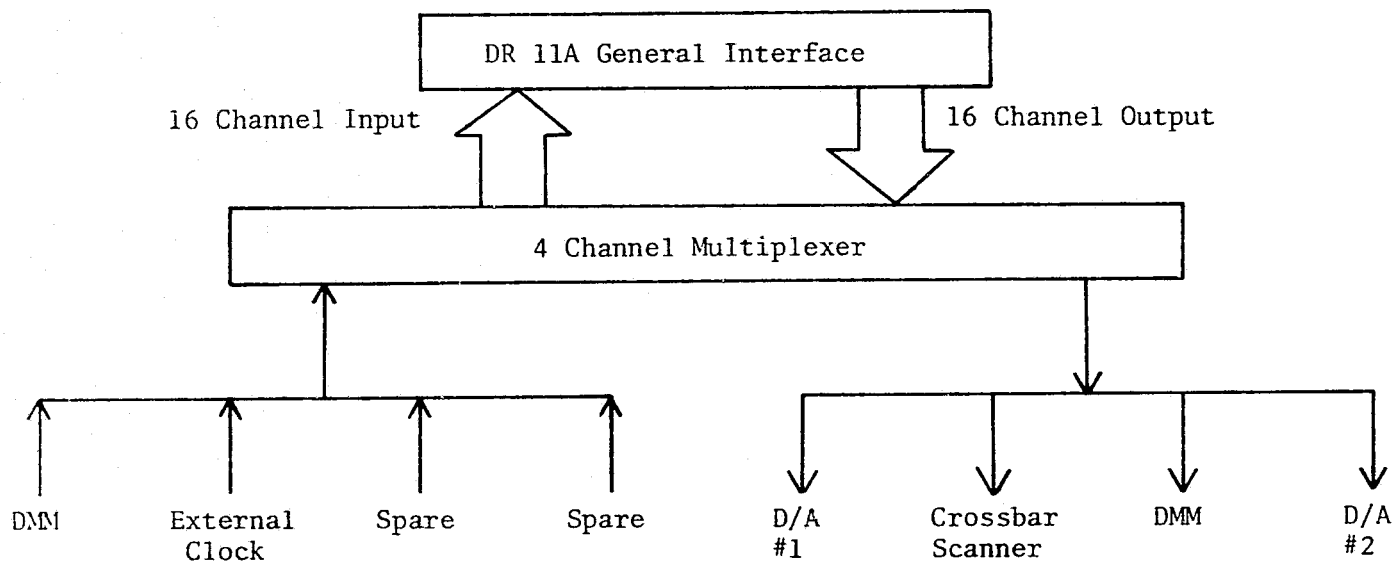


Figure 2.7. General Purpose Interface Diagram

with the data acquisition unit for various testing functions. A version of the Dartmouth BASIC programming language coupled with a machine language instruction set makes the processor an effective hybrid system for monitoring or controlling the thin film deposition process.

This chapter has described the hardware involved in both the monitoring and controlling phases of the deposition process along with the integral hardware required to carry out the actual deposition process. The following chapters will describe the techniques and algorithms capable of monitoring and digitally controlling the deposition process.

Chapter 3

MONITOR TECHNIQUE

As indicated in Chapter 1, the problem being considered entails three aspects, i.e., the development of the hardware to monitor and control the deposition process, the development of the procedure and software to monitor the deposition process under control of the analog unit, and the development of the procedure and software for an analysis of the digital control technique. The first aspect, the hardware to monitor and control the process, was discussed in Chapter 2. This chapter will explain the monitoring technique used to gather information from the analog system.

It should be noted that the monitoring technique described in this chapter is similar to the technique used to acquire data for the controlling process. The primary difference between the monitoring phase and the control phase is that the monitoring technique described in this chapter is written primarily in BASIC, while the monitoring software used in the digital control section is written in a Programmable Assembly Language (PAL).

Two parameters of interest during the deposition process are the rate of deposition and the input signal to the SCR power controller. The deposition rate is desired in order to have a reference for comparing the effectiveness of the digital controller versus the analog controller and because it is the primary function controlled. The input signal

to the SCR power controller is an indicator of the response of the deposition rate output to a given input.

The function of the monitoring algorithm is to measure the frequency shift from the quartz-crystal monitor and the SCR power controller at fixed intervals of time, calculate a rate of deposition, and "massage" the data for output in various formats under user control. For accuracy, the DC output of the quartz-crystal monitor unit is used as the source of the low frequency shift data, while a direct connection to the inputs of the SCR power controller acts as the second source. Both signal sources are connected to separate input channels of the crossbar scanner for access by the DMM under control of the digital processor. Using the external digital clock to obtain an accurate and equally spaced measuring sequence of one set of data per second, the digital processor, through the use of the BASIC program (Appendix A), periodically collects the data from the two sources.

To accomplish the monitoring of a particular deposition run under control of the analog controller, a BASIC program, interfaced with an assembly language program, is utilized. Figure 3.1 illustrates the flow diagram for the monitoring procedure. Initialization of the variables, such as the number of seconds of monitoring, is input into the algorithm via the teletype. Once execution commences, the BASIC program retains count of the number of samples taken while an EXTERNAL FUNCTION routine, which is explained later in the chapter, monitors the digital clock input until a pulse is received. Upon receiving the signal, the algorithm transfers control from the clock monitoring routine to the routine that sets the crossbar scanner to the proper channels, polls the digital multimeter for the voltage value of the DC signal and the

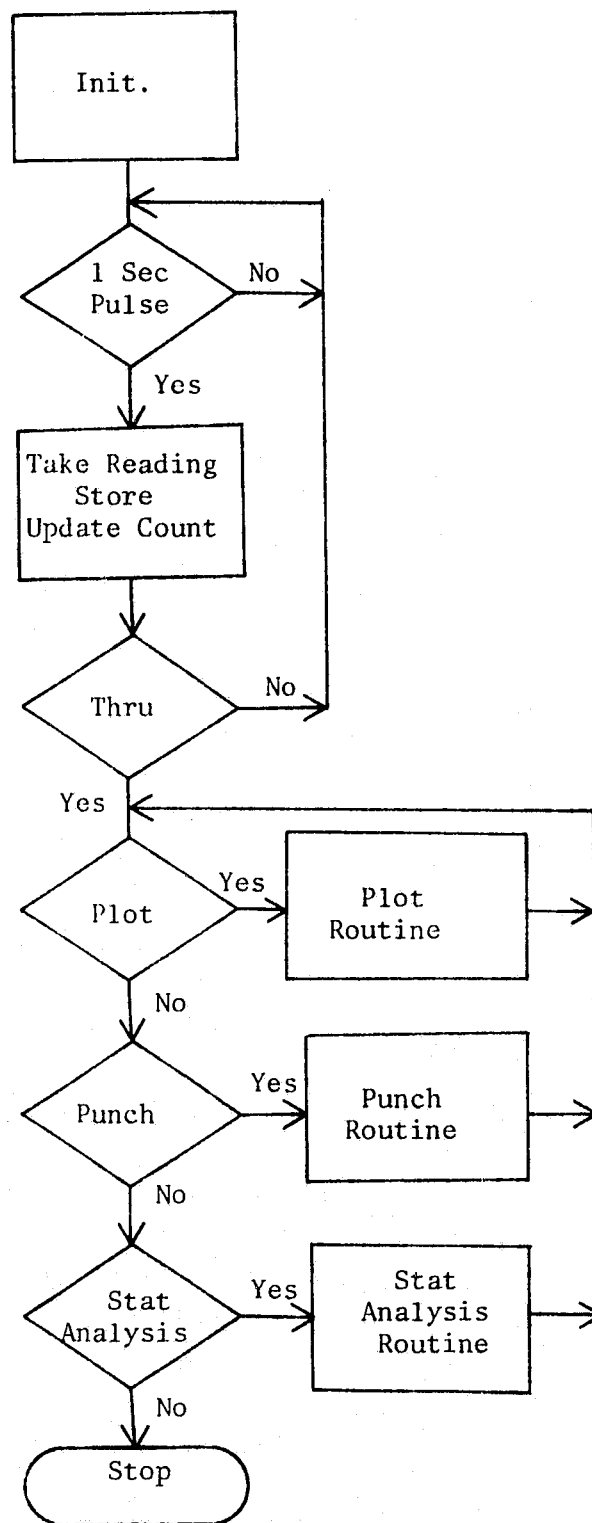


Figure 3.1. Monitoring Routine Flow Diagram

SCR power setting, stores the results internally in memory, updates the sample counter, compares this count with the desired count, and either transfers control to the clock monitoring routine or "drop" through to the output portion of the routine. At the drop through point of the algorithm, a decision to choose a rate or SCR plot, a punch tape, or the statistical analysis of the data has to be directed to the processor via the teletype input.

Prior to the execution of the plotting routine for the rate data, the DC voltage data corresponding to the measured frequency have to be digitally differentiated with respect to time to obtain the data in terms of rate units. Using the time interval between sampling as the base time for differentiation, the rate of change of the DC signal per second can be calculated using the relation

$$\frac{\Delta(\text{DC})}{\Delta t} = V_i - V_{i-1} \quad i = 2, 3, 4, \dots \quad (3.1)$$

where V_i is the voltage reading obtained from the frequency to DC converter at the i -th second. In order to convert (3.1) to units that have meaning, i.e., Hertz or Angstroms/sec., the voltage values have to be multiplied by a constant of proportionality

$$\frac{\Delta(\text{FREQ})}{\Delta t} = \text{Rate } i = M1 \cdot (V_i - V_{i-1}) \quad i = 2, 3, 4, \dots \quad (3.2)$$

where $M1$ is the proportionality constant. The value of $M1$ in Hz/sec can readily be obtained from the slope of the calibration curve shown in Fig. 3.2(b). By multiplying this value of $M1$ by the corresponding evaporant slope of the Hertz-Angstrom curve, Fig. 3.2(a), the rate in

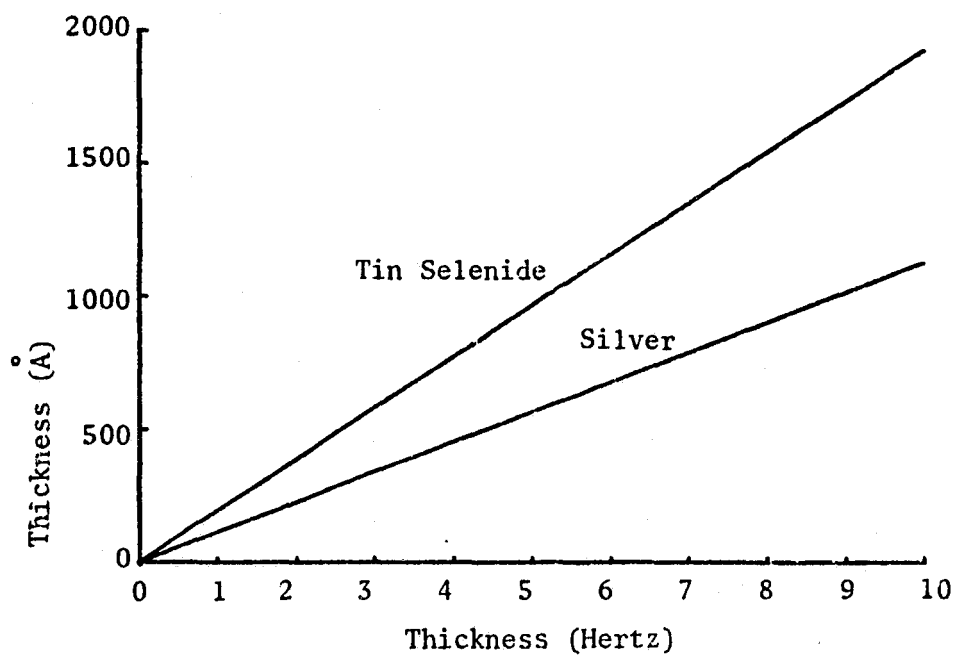


Figure 3.2(a). Thickness Conversion (Angstroms-Hertz)

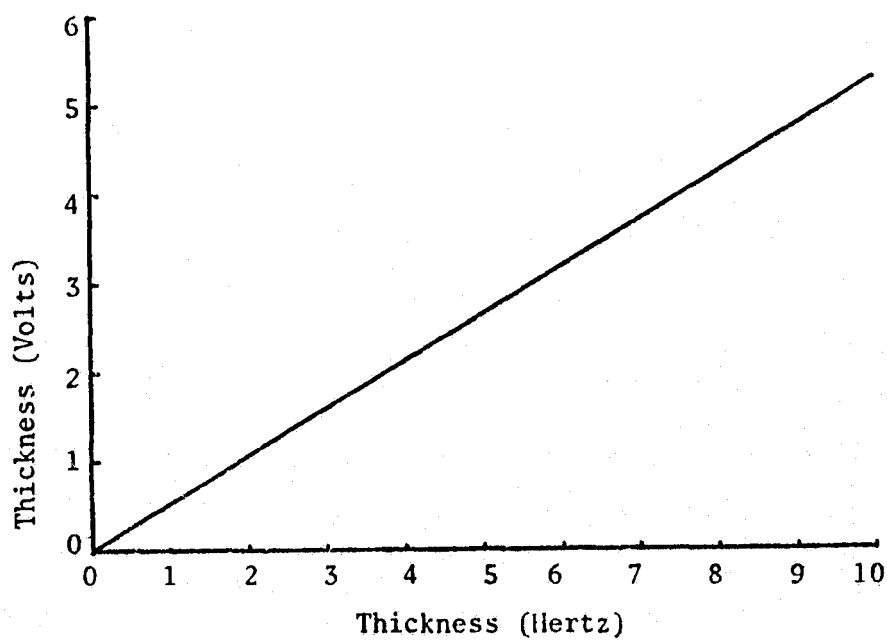


Figure 3.2(b). Thickness Conversion (Volts-Hertz)

Angstroms/sec can be obtained. Since the slope of the DC conversion to Hertz is independent of material, while the Hertz-Angstrom curve is dependent upon the density of the evaporant material, the primary analysis conducted in later chapters is with reference to the Hertz relationship in order to give a common base for the analysis.

The conversion of the frequency data to rate data is needed for two purposes. The first is to plot the rate, along with the SCR power controller input, throughout the deposition process for use in analysis of the data. The second purpose is to be able to perform statistical analysis upon the rate data and establish a mathematical basis for comparison of the two controller techniques.

To perform the statistical analysis, routines to calculate the mean value of the rate and the standard deviation about the mean are incorporated as part of the analysis routine. The rate data calculated from (3.2) are used to obtain the standard deviation through the relationship

$$\mu_R = \frac{1}{K_2 - K_1 + 1} \left[\sum_{i=K_1}^{K_2} R_i^2 - \frac{\sum_{i=K_1}^{K_2} (R_i)^2}{K_2 - K_1} \right]^{1/2} \quad (3.3)$$

where μ_R = Standard deviation of the mean rate

R_i = Rate at the i -th second

K_2 = Last rate data point

K_1 = First rate data point

The mean value of the rate, R_{12} , over the time interval $K_1 + 1$ to

K_2 , can be calculated using the rate value of (3.2) substituted in the statistical mean equation, i.e.,

$$R_{12} = \frac{1}{K_2 - K_1 + 1} \sum_{i=K_1+1}^{K_2} R_i \quad (3.4)$$

Simplification of (3.4) can be made by substituting (3.2) to obtain,

$$R_{12} = \frac{1}{K_2 - K_1 + 1} \sum_{i=K_1+1}^{K_2} (M1 * (V_i - V_{i-1})) \quad (3.5)$$

or expanding (3.5) we obtain

$$\begin{aligned} R_{12} = \frac{1}{K_2 - K_1 + 1} & (V_{K_1+1} - V_{K_1}) + (V_{K_1+2} - V_{K_1+1}) + \dots \\ & + (V_{K_2-1} - V_{K_2-2}) + (V_{K_2} - V_{K_2-1}) \end{aligned} \quad (3.6)$$

Examining (3.6), it can easily be seen that the positive term in every group is cancelled by the negative term in the succeeding group except for the last group. Carrying out the subtraction, (3.6) will reduce to

$$R_{12} = \frac{M1}{K_2 - K_1 + 1} [V_{K_2} - V_{K_1}] \quad (3.7)$$

Thus, to calculate the mean value of the rate signal over a given time interval only the voltage measurements at each end of the interval are needed.

After the plotting of the rate data and SCR data along with the statistical analysis of the rate data, see for example the run illustrated

in Fig. 3.3, the internally stored raw data are punched on paper tape using the high speed punch. This results in a permanent copy of the data that can easily be "read" by the digital processor.

The routines described, including the algorithms for the statistical analysis, are performed by the previously defined hardware under software control. As explained, a hybrid choice of software, i.e., BASIC and PAL, was chosen. The choice of using BASIC as the primary language for the monitoring phase was based on the ease of constructing and editing a BASIC program. Since the only function being completed during each second of monitoring consisted of storing in memory the two DMM readings, slow execution speed of BASIC did not have an effect on the choice of languages. However, speed of execution had to be considered in the choice of the PAL programs interfaced with the BASIC routine.

The EXTERNAL FUNCTION call, the method by which BASIC programs are interfaced with a machine language portion, allows the user to write subroutines in the machine's language instruction set in order to increase the speed of an operation. As an example, to calculate the statistical analysis for a 550 second deposition period, a routine written in machine language requires less than 20 seconds.

Since the routine was rigidly fixed for the statistical analysis portion of the routine, the added effort required to program in PAL was worthwhile. However, writing the entire program in PAL while maintaining the flexibility which allowed ease of editing was not possible. Thus, a hybrid set of software maintaining the speed in redundant operations and the flexibility for user augmentation was used.

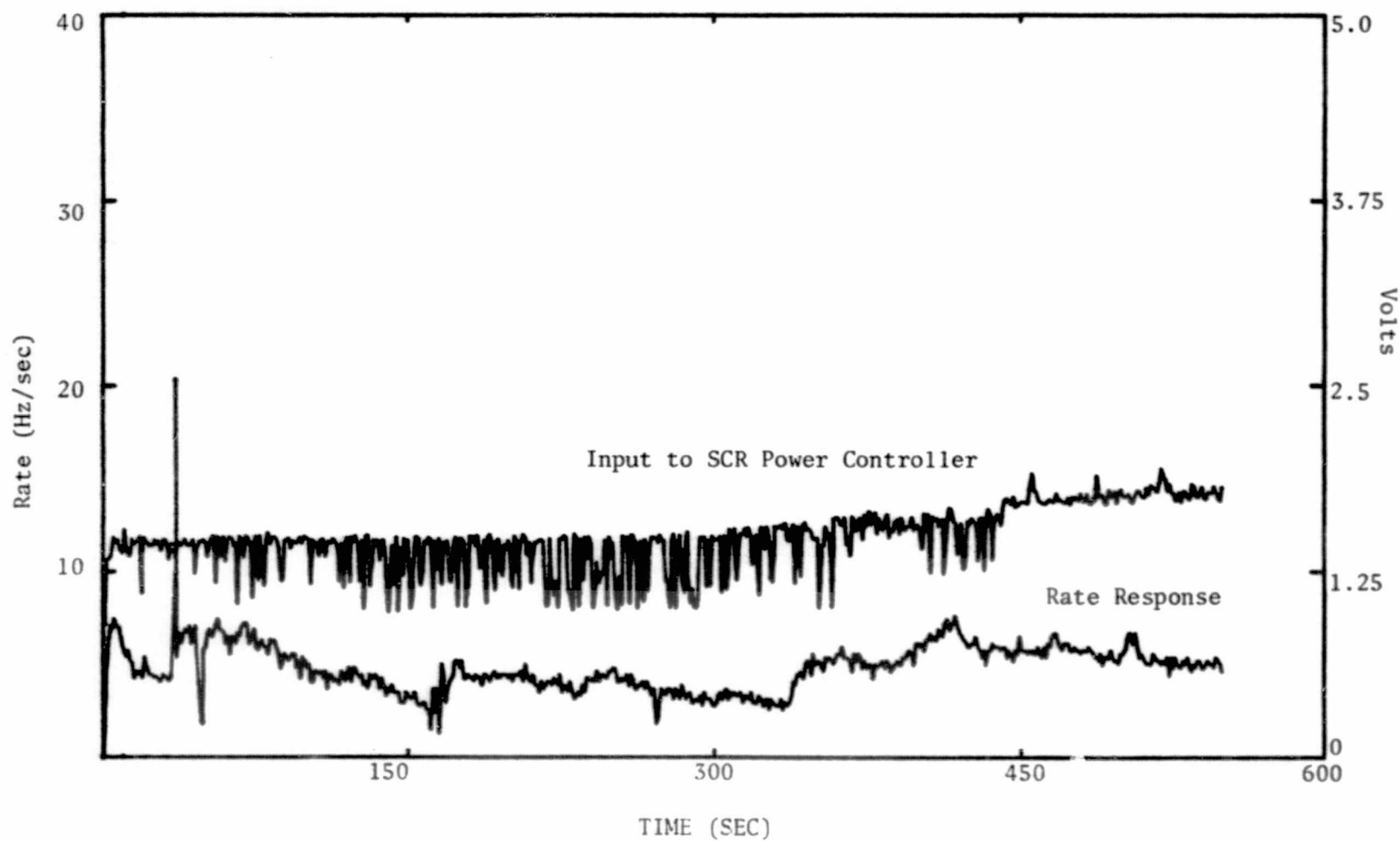


Figure 3.3. Deposition Measurement Mode with Monitoring Hardware

This chapter has illustrated the monitoring technique used to obtain data for both analysis of the system and as a base of comparison. The algorithm required to monitor a deposition and plot and analyze the data has been given. The next important factors to consider are the algorithms and routines needed to implement the digital controller and close the feedback loop of the deposition process.

Chapter 4

CONTROLLER DEVELOPMENT

Once the hardware and software requirements necessary to allow monitoring and controlling of the deposition, as described in previous chapters, have been dictated, the software algorithm to close the control loop through the digital processor needs to be developed and implemented. This chapter will establish the control algorithms that were investigated along with associated problems encountered and their solutions. Initial studies indicated that because of the complexity of the system, as indicated in Chapter 2, an adaptive controller was desirable. With this approach selected, a scheme similar to the work of Kalman [13] was investigated. To control a second order system Kalman developed an algorithm that resulted in minimum time to steady state with minimum overshoot. He illustrated his technique using a second order system as illustrated in Fig. 4.1.

Mathematical approximation of the deposition system implied a second order system was the appropriate model. This hypothesis resulted from an analysis of each subsystem by estimating its response to a step input. For the second order closed loop control system illustrated in Fig. 4.1, the control law established by the Kalman technique had the form:

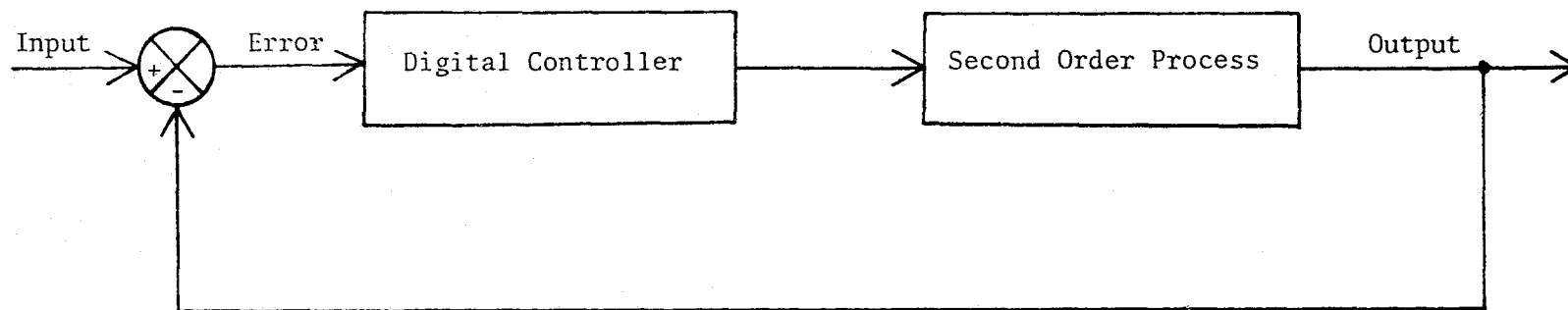


Figure 4.1. Block Diagram of Second Order Control Process

$$\begin{aligned}
& [a_1(N) + a_2(N)]M_k - a_1(N)M_{k-1} - a_2(N)M_{k-2} \\
& = e_k + b_1(N)e_{k-1} + b_2(N)e_{k-2}
\end{aligned} \tag{4.1}$$

Where

a_1, a_2, b_1, b_2 = the adaptive coefficients to be updated periodically,

M_k = the controller output at the k -th sample,

$e_k = r_k - c_k$ ($k=1,2,3,\dots$) = the system error at the k -th sample,

r_k = desired rate value at the k -th sample, and

c_k = measured rate value at the k -th sample.

By manipulation of (4.1), the controller output for a given sample can be calculated by

$$\begin{aligned}
M_k = & [a_1(N)M_{k-1} + b_1(N)M_{k-2} + e_k + b_1(N)c_{k-1} \\
& + b_2(N)e_{k-2}] / [a_1(N) + a_2(N)].
\end{aligned} \tag{4.2}$$

Therefore, the controller output as described in (4.2) is a function of the history of the past controller outputs, M_{k-1} and M_{k-2} , along with the influence of the present errors, e_k , and the past errors. Kalman proved that for a second order system the adaptive coefficients should be updated every third sample period. That is, the controller uses a set of adaptive coefficients to control the process for three time periods and between the third and fourth period a new set of coefficients is calculated.

His work indicated that the algorithm was independent of the initial values chosen for the coefficients, but that after a short processing time, the coefficients would converge to a set of values

that would drive the system to the desired response. If the initial coefficient values were not close to the steady state values, an unstable response could occur. Assurance that the controller was inherently stable and that the coefficient would converge was given by Kalman.

After incorporating the Kalman adaptive coefficient controller in the software of the digital processor, many attempts were made to achieve the indicated success that Kalman experienced. Theoretically, the technique should have worked but in reality results less than optimal were obtained. Allowing the adaptive controller to operate with no restrictions on any of the coefficients or control outputs, the algorithm should have driven the coefficients to the necessary values to achieve the desired control characteristics. Initial processing with the controller in an unrestrictive mode resulted in unsuccessful control in that the coefficients were not converging toward a set of values nor was stability being achieved.

Analysis of the controller response to calculated error signals indicated that the controller was attempting to obtain control by driving the system in the proper direction to achieve the desired response. After a period of time, the system response due to high output values from the controller were beyond the measuring constraints of the hardware. At times, due to low indications, the controller would calculate SCR power settings that would turn the electron gun on full power, a condition that would soon burn out the gun and crucible assembly. At the high output setting, the system would attempt to achieve a rate so high that material would literally boil out of the crucible. A software constraint to limit the maximum controller output appeared to prevent overloading of the electron gun.

Initial constraints limiting the minimum and maximum values the controller could transmit to the D/A unit had shortcomings in that this did not appear to give the adaptive process the freedom to operate in an unrestrictive mode. Some convergence was experienced by the new technique, especially for initial coefficients near a stable condition, but the response was inadequate as a replacement for the analog rate controller.

As a corrective measure, instead of calculating a new D/A setting at the end of each controller sample, as indicated by (4.2), a "delta" change to the previous controller setting was calculated. This technique, coupled with the maximum/minimum controller restriction, would allow only a small change to be added or subtracted from the past D/A setting.

To incorporate this change, the D/A input value at the end of the soak routine was stored within the memory. At the completion of a controller calculation the output was compared with the maximum/minimum restriction and the resultant correction added/subtracted to the D/A setting. That value was then passed to the D/A input and into the memory for use at the end of the next controller calculation. Mathematical changes were made to (4.2) to obtain the new control algorithm:

$$\Delta M_k = [a_1(N)M_{k-1} + b_1(N)M_{k-2} + e_k + b_1(N)e_{k-1} + b_2(N)e_{k-2}] / [a_1(N) + a_2(N)] \quad (4.3)$$

Several deposition attempts using (4.3) as the control law brought results similar to those experienced previously. Analysis of the rate response and the controller output indicated that initial coefficient

values could be chosen to generate stable responses. During the successive control calculations following an update the output would take a significant jump on the first sample and then slowly take insignificant adjustments in an attempt to drive the response toward the desired value.

This problem appeared to be due primarily to the system's not having enough time to respond to the controller output. Since the adaptive coefficient process relied upon the response of the system to the output, a one second sample time for a system taking several seconds to respond to a given input was insufficient. With a software modification, the controller was adapted to take rate data at one second intervals while the controller output time interval was periodically updated as dictated by the user.

Software restrictions required that the sample time be taken in multiples of three seconds, i.e., on the first, fourth, seventh, etc., seconds of processing. This restriction was because of the necessity of placing the proper k-th error and post error in the correct sequence of the software.

Attempts at varying the sample time also met with limited success. Restrictions on the amount of variations in the coefficients, selection of coefficients, update or sample time variation, and restriction of the amount of change between control settings had little effect on the convergence/divergence of the coefficients. A detailed analysis of the software indicated that a problem existed in the implementation of the software in the digital processor. Hardware restrictions on the processors' word structure placed a limitation on accuracy which could be expected from the calculations involving very large and very small values. When this limitation was applied to the matrix inversion

routines used to update the coefficients, it was noted that the accuracy needed to perform the inversion was not within the scope of the software or hardware of the DCU.

Because of the numerical limitations that restricted the use of the adaptive process originally proposed, a fixed coefficient controller was implemented. Using the basic control law established in (4.3) along with successive iteration of the coefficients, attempts were made to tune the fixed coefficients. Based on the response of the controller with the human factor in the feedback loop to update the coefficients, a set of coefficients was derived that appeared to give reasonable control of the deposition process. Although the control was inferior to the analog rate controller, it appeared to be the best that could be achieved from the given algorithm.

An analysis of the response of the controller is illustrated in Fig. 4.2. The characteristics of the algorithm indicate a predominant lag between the response and the input. This resulted in the controller's always overreacting to the response of the deposition process. When the rate exceeds the desired rate, as shown in Fig. 4.2, the controller does not cut back on the input power until the response has passed through the desired rate. For a fast responding system this controller would normally be damped. However, for a slow responding system such as the deposition system an adequate damping factor could not be achieved.

Various parameter variations were implemented in an attempt to increase the damping factor while maintaining a marginally stable system response. After attempts to tune the coefficients were unsuccessful it was decided that possibly the type system had been erroneously chosen

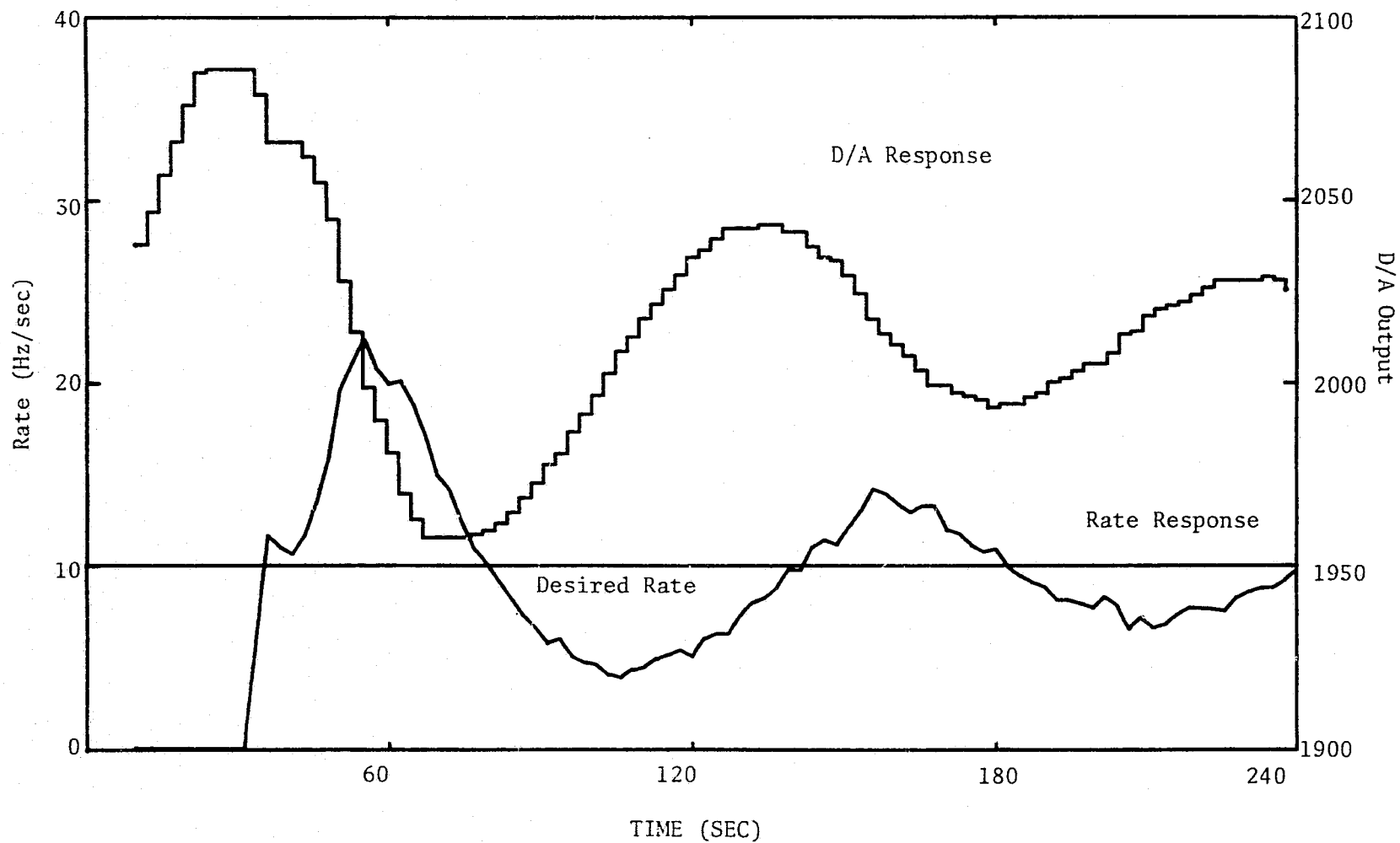


Figure 4.2. Phase Lag Controller Response

or that the chosen coefficients were far from the correct coefficients required for stability.

Further analysis indicated that control might be obtained if the controller could sense the rate of change of the response and adjust accordingly. With this hypothesis formulated, a new algorithm was developed. Assuming a controller output proportional to the error and rate of change in the error, the following algorithm was obtained.

$$\Delta M_k = e_k + W \cdot \dot{e}_k \quad (4.5)$$

where W is a coefficient that determines the effect of the rate term on the output. Known as a Lead Phase Compensator, (4.5) describes an algorithm which has the properties of improving the time response of the system by the introduction of anticipation into the controller.

Implementation of (4.5) into the software can easily be achieved by setting the values of (4.4) to:

$$\Delta M_{k-1} = \Delta M_{k-2} = 0 \quad (4.6a)$$

$$a_1 = a_2 = 1 \quad (4.6b)$$

$$b_2 = -b_1 = W \quad (4.6c)$$

$$e_{k-2} = e_k \quad (4.6d)$$

Thus, (4.4) becomes

$$\Delta M_k = e_k + W(e_k - e_{k-1}) \quad (4.7)$$

which is the digital representation of (4.5) for implementation in the processor.

The first attempts to employ (4.7) brought successful results well beyond those achieved with any other technique that had been previously investigated in this work. The controller was able to control the response of the deposition process to the desired degree while maintaining it within a small variation about the mean.

Variation of the velocity multiplier, W , indicated that the stability of the control process had a dependence on the velocity parameter. Test runs with both a metal (silver), and a semiconductor (tin selenide), were conducted to determine the dependency of the stability on the velocity term. The standard deviation measurement about the mean was used as the measurement indicator. Initial test runs indicated dependency of the controller on both the sample time and the velocity multiplier. Thus, the tests were modified to incorporate the sample time variation as one of the dependent variables.

This chapter has illustrated the evolutionary process which the digital controller algorithm underwent to reach the form of (4.7). The following chapters will explain the software used by the digital controller and the results of the parameter tuning effort along with the results of the final control algorithm.

Chapter 5

DIGITAL CONTROLLER SOFTWARE DESCRIPTION

This chapter will describe the software methodology utilized to incorporate the control algorithm established in Chapter 4. The software written to control the deposition process differs from the monitoring software primarily by the type language used to implement each. In the case of the monitoring software, a hybrid combination of the conversational language, BASIC, and the machine language, PAL, was incorporated for ease of programming.

To implement the control process, only the machine language, PAL, is used in order to facilitate the speed asset that can be obtained. Besides taking the frequency measurement in the one second interval, the control algorithm calculates a rate based on the frequency measurement, calculates a D/A setting based on the rate error, adjusts the multiplexer to receive and transmit the proper data, sets the D/A input to the calculated value, and, finally, punches all the data on the high speed punch. Thus, it becomes apparent that speed of execution is the primary driving function for the choice of the machine language.

To illustrate the speed that can be expected from the processor, the nominal instructions including single word adds, subtracts, compares, and branches require approximately 1.5 microseconds for execution. Coupled with a floating point math package capable of performing floating point operations in milliseconds, the language structure lends itself to sophisticated programming.

Not only are algorithms to take voltage measurements, to calculate rate values, and to calculate control outputs needed to complete this task, but support algorithms to perform the rise, soak, data punching, and other "housekeeping" functions are required for a unified software package. Figure 5.1 depicts the organizational structure of the finished software package. A description of each of the modules in the figures, along with the interaction of each, will be covered in this chapter. A listing of all the routines is contained in Appendix B.

SOFTWARE MODULE DESCRIPTION

To have a dynamically interactive software structure, that is, one that interacts with the user during execution, a structure based on a priority interrupt system was developed. Assigning priority of execution to different devices such as the teletype, digital clock, high speed punch, D/A, and power fail hardware, required software that relies on an interrupt signal from a given device. This was developed to effectively and efficiently incorporate the associated service routines. To illustrate, the power fail has top priority which means that whenever this device interrupts the process, any routine being executed will stop and allow the power fail routine to be executed. If a device of priority level equal to the device being serviced attempts an interrupt, the interrupting device will have to wait.

The interrupt controller, illustrated in Fig. 5.2, will be the first module considered. The interrupt controller is composed of the teletype, the pulse clock, the initialization routine, and the trap handler. The first routine entered on loading the program is the module titled MAIN, which initializes the hardware by setting the proper channel

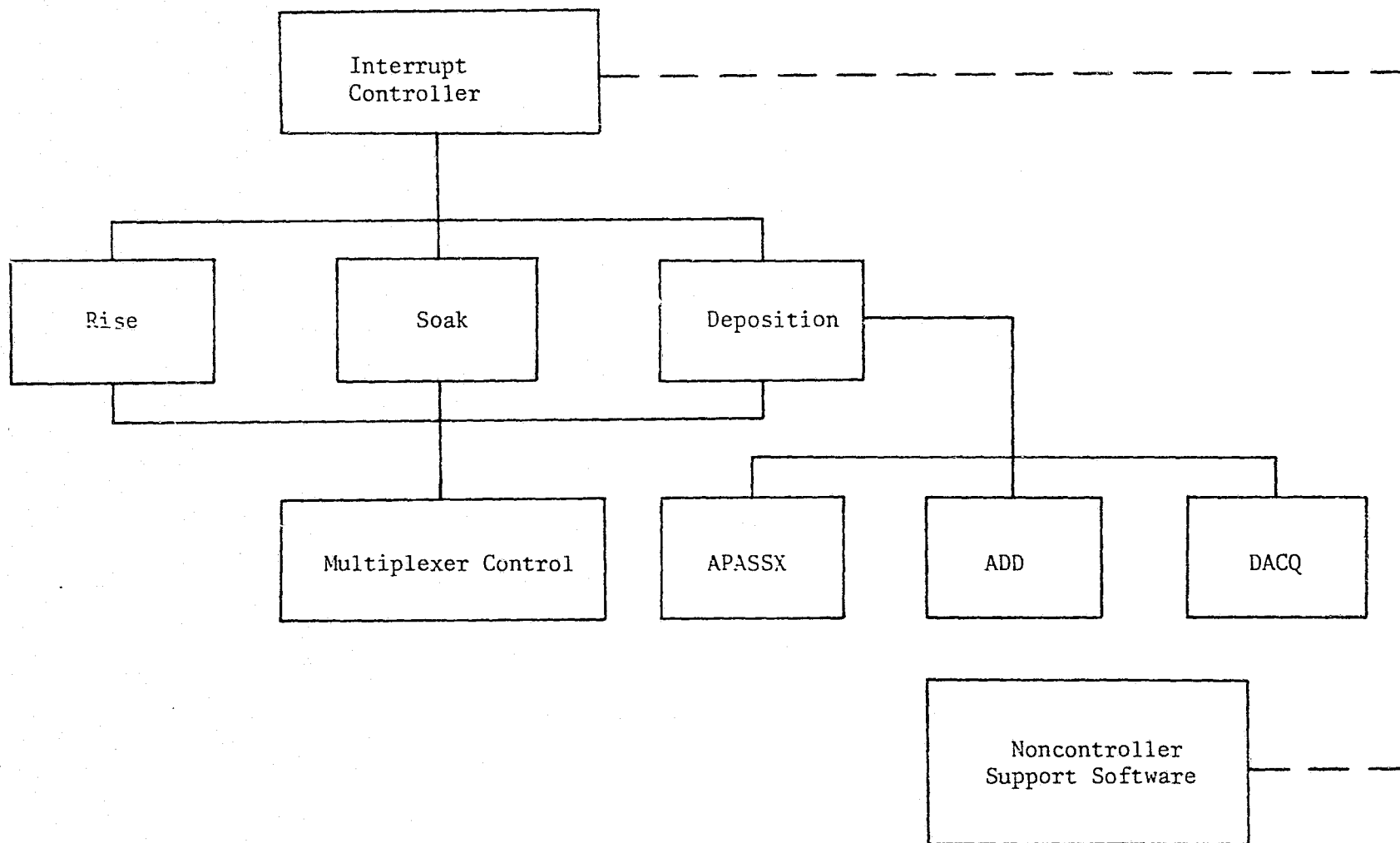


Figure 5.1. Digital Controller Software Structure

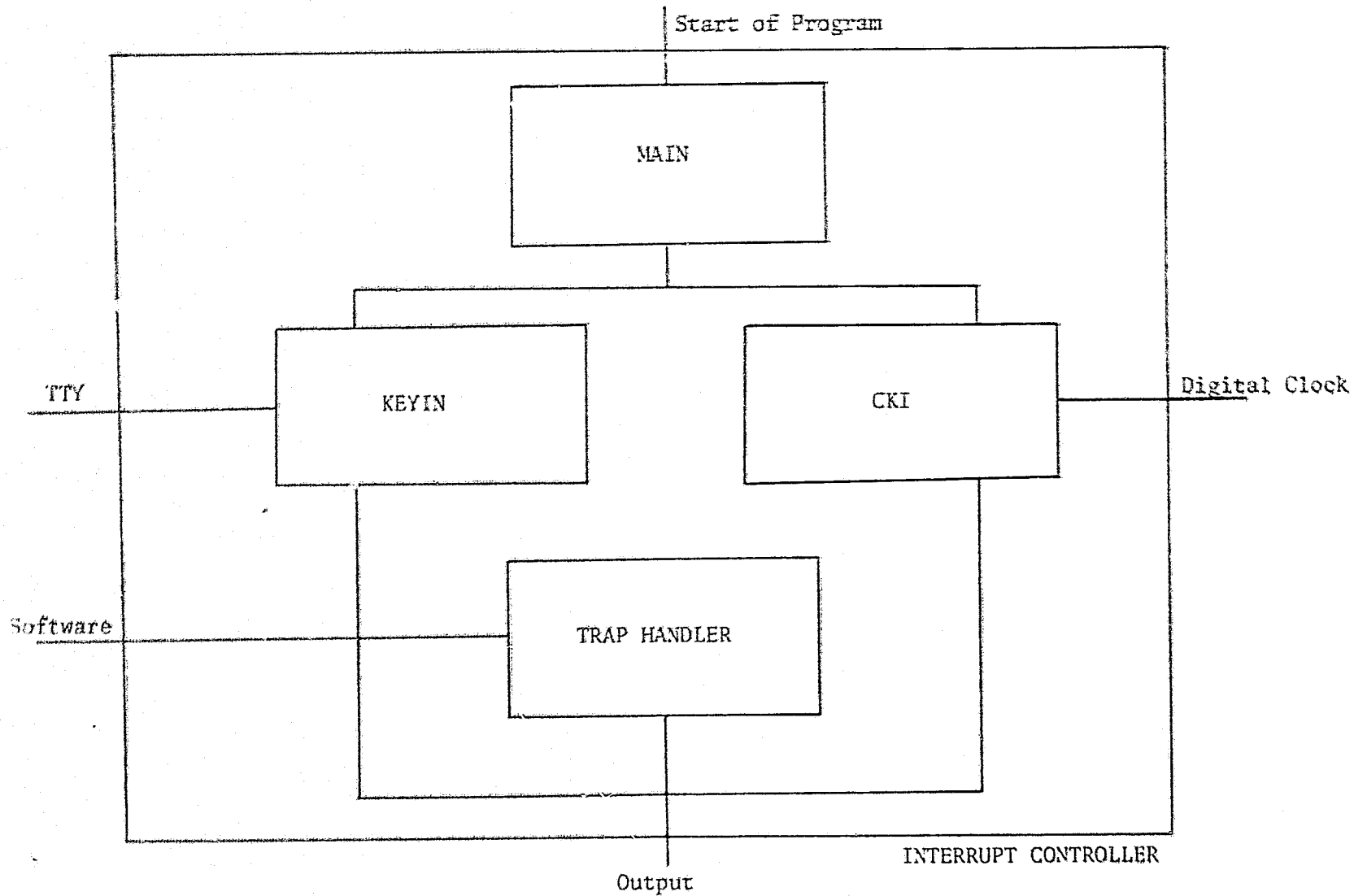


Figure 5.2. Interrupt Controller Block Diagram

on the D/A unit, encodes the DMM to take a voltage reading, and finally transfers control to the next module, KEYIN. The MAIN routine, entered each time the clock pulse causes an interrupt, determines the deposition status.

After hardware initialization is completed, the teletype interrupt enable line is made available. Any time a character is struck on the teletype, a hardware interrupt is sensed by the processor. If there is no other routine being executed with a higher priority, the KEYIN routine is entered and the character which is struck is evaluated. If the character isn't recognized as a (CTRL P), (control "P"), KEYIN ignores the input. Entering CTRL P and having it evaluated results in a response from the processor to the user. The colon symbol, ":", is output to the teletype and control is transferred to the INPUT/OUTPUT EXECUTIVE, (IOX) which operating in an interrupt mode receives, echoes, and stores in memory any inputs from the teletype. Once the return key, symbolizing an end to the input, is entered IOX returns the message to KEYIN for evaluation. Thus, KEYIN, coupled with the IOX routine and operating in an interrupt mode, relieves the processor from continually monitoring the teletype for an input and allows entry to software when no other routines are being executed.

It is through the KEYIN routine that the variable data for the coefficients of the controller, the time variables such as rise, soak, and deposition time, the punch requirements, the execution commands, and the desired rate of deposition are input to the processor via the teletype. Not only can the variables be input via KEYIN, but the values of the input parameters can be verified through the same routine.

Since it is an interrupt-controlled software structure, the processor can be polled at any time by the user via the teletype with a subsequent change entered for one of the variables. As an example, during the deposition routine, if it is desired to change the rate of deposition, redefining the rate variable results in that variable's being immediately changed. The next calculation of an error signal for (4.7) will use the newly updated value.

KEYIN is the base module that accepts the commands of parameter definition, parameter status, or process definition. Without the interactive capability or the parameter assignment that KEYIN offers to the software package, any paramount variation would have to be binarily entered via machine language modification versus the convenient conversational mode.

As KEYIN functions to interpret commands from the teletype interrupts, the clock interrupt routine (CKI) functions similarly to interpret interrupts from the clock and select the proper service routine, i.e., rise, soak, deposition, or standby. During the execution of the program, one second pulses are sent from the external clock to the CKI routine. If the deposition process had been started, each clock interrupt would cause one of the above routines to be entered based on the condition of the flag settings within CKI. CKI directs the flow of the processor every time a clock pulse is sensed by the hardware.

The last routine within the Interrupt Controller is the trap handler routine which evaluates all the internally generated software traps. It performs standard software functions such as floating point manipulations, error message generation, and teletype input/output executive manipulation. Upon completion of the execution of a generated

trap routine, as in all the interrupt controller modules, the interrupted process is resumed.

Control from the interrupt controller is passed to the rise, soak, deposition, or support software module for execution of a given function. Each of these modules will now be discussed with explanation of the function performed by each.

Rise

The RISE routine is incorporated to set the electron gun to a given power setting below deposition power and raise the power slowly to a soak setting sufficient to outgas the evaporant. From parameter values input to the routine via KEYIN, an initial and final power setting is calculated and stored in the process's memory. Upon entering the rise routine, an incremental increase for each time interval is calculated using the relation

$$\Delta D/A = \text{Integer} \frac{R_F - R_I}{T_R} \quad (5.1)$$

where R_F = Final Rise Value

R_I = Initial Rise Value

T_R = Rise Time (seconds).

The initial value, R_I , is transferred to the D/A thus establishing an initial power setting for the electron gun. At each one second interval, the D/A value is updated to a new value dictated by the prior setting plus the integer incremental value formulated by (5.1).

Evaluation of (5.1) will show that unless caution is taken so that the division process results in an integer value the final rise setting will be less than the desired value. As an example consider R_F ,

R_I , and T_R to be 440, 240, and 60, respectively. Carrying out the calculation yields an incremental value of 3.333 units per update. Taking the integer value yields an operating incremental value of 3, which results in a final value of 420 instead of the desired 440. This minor limitation is not significant when compared to the time restriction the analog controller places on its rise routine. Using the analog controller a maximum rise time of 180 seconds can be achieved. However, using the digitally controlled rise routine a maximum rise time of 2^{16} seconds or 655,335 seconds can be achieved. For materials requiring long rise times such as quartz or platinum, the digital processor offers a definite advantage.

Soak

When the count, kept by an internal counter updated each clock pulse, reaches the set value for rise time, T_R , the rise flag is cleared and the process is transferred to the Soak routine along with the final rise value of the D/A. Similar to the Rise routine in the operation, the Soak routine maintains the final rise setting for a prescribed time, T_S , allowing the evaporant to complete the outgassing process. The Soak routine also offers the advantage that T_S can have any value up to 65,535 seconds.

Deposition

After the Soak routine has been executed for the preset time, control along with the D/A setting is passed to the deposition routine (DEPOS). Within DEPOS the digital control of rate parameter is executed. The control law equation developed in Chapter 4 is implemented by DEPOS with the aid of support software. Routines controlled by DEPOS perform

hardware manipulation, frequency calculations, and other "housekeeping" functions. It is within DEPOS that the control value output is compared with the maximum or minimum allowed value and the result transferred to the D/A.

Other functions completed by DEPOS include the calculation of the rate, the error, and the rate of change of error. At the end of each of the three time intervals of data processing, DEPOS structures all the parameter values, rate, D/A settings, and variable coefficients for punch by the HSR/P. In the interrupt mode, the processor passes a word of information to the HSR/P and then continues to process other routines until the punch interrupts the processor and requests more data. This "hand shaking" routine continues until all the data is punched on the tape.

In order to maintain modules of reasonable length, the DEPOS module has several support modules directly coupled as illustrated in Fig. 5.1. The largest of the support modules is APASSX which is tasked to calculate the error and the digital controller increment. In a support role via DEPOS to APASSX is the ADD module which algebraically adds the calculated controller increment to the previous controller output which is sent to DEPOS for comparison and finally transferred to the D/A unit.

DEPOS relies on the support module DACQ to perform the function of controlling the A/D unit. After supplying software codes which are compatible with the required hardware inputs, DACQ monitors the DMM until a measurement is completed. It then "reads" the data from the digital output and converts it to a format for utilization by DEPOS. Therefore,

the interaction of DEPOS with its support modules, APASSX, ADD, and DACQ, completes the software manipulation needed to calculate control values.

Interface Controllers

Illustrated in Fig. 5.1 are the interface control modules which are common to all the processing routines. The CTIMDX, which can be entered from either the rise, soak or deposition routine indicating which devices require access from the processing routines. It then sets the proper channels on the four channel multiplexer allowing access through one DR11-A general interface input/output device to branch to four real world hardware devices.

Noncontrolling Support Routines

Also shown in Fig. 5.1 by the dotted lines are modules referred to as Noncontrolling Support Software. These modules, Power/Fail and DEBUG, are routines which support the total effort out are not directly utilized by the digital processor to complete the deposition control. The Power/Fail routine supports the processor in case the line voltage is interrupted during processing. Once the line voltage drops an interrupt with top priority is generated that gives the power/fail routine 2 milliseconds to perform its functions. In the 2 milliseconds all the working registers are stored in nonvolital memory. On power recovery, the routine resets the channel on the crossbar scanner and institutes a DMM reading to make sure all the hardware is set as it was prior to the power/fail. After the hardware is reset, all the working registers are restored and execution of the deposition program continues. This routine has proven itself valuable especially during thunderstorms where line flickers occur regularly.

The other routine which has been very valuable in debugging any software modification or changing any coded variable is the DEBUG module. On initial loading of the entire software into the machine, transfer is automatically made to the DEBUG module. The sample time, as discussed in Chapter 4, along with the starting address of the digital controller routine are input through DEBUG and transfer is made to MAIN.

When access is required of DEBUG, the KEYIN routine, coupled with the statement "DEBUG" typed through the teletype, causes transfer of execution to the debug package. DEBUG gives the user the capability of polling the contents of any memory location and having its contents printed on the teletype. If it is desired to change the polled contents, entering the desired contents on the keyboard will result in the value being inserted in the proper location.

Termination Modes

There are two possible ways to terminate the control process. One which is used extensively in the coefficient determination effort is a fixed-time mode for deposition. The fixed-time mode is implemented by placing a finite deposit time into the system. At the completion of the time span, the deposition is terminated and a message is printed out on the teletype. This mode results in equal deposition periods required for analysis purposes.

The alternate mode of termination, which is most advantageous for thin film device manufacture, is the fixed thickness mode. Once the deposition has started in this mode, the operator inputs a value for the end frequency which corresponds to a finite thickness. As an example, if a frequency shift of 10 KHz represents a desired thickness of 5000 Å

and the presently displayed frequency value is 1500 Hz, a thickness value of 11,500 is entered via KEYIN along with a very high deposition time. When the frequency measurement reaches 11,500 Hz, the deposition process will cease.

Summary

All the routines discussed comprise the digital software structure used to control the rate parameter for the deposition of thin film devices. A synopsis of each module is presented in Table I.

As previously indicated, initial data has to be input to the algorithm prior to execution of the digital controller; see user example in Appendix D. Table II presents a complete listing of all the variables which must be initialized along with the variables which can be polled for deposition status. For example, if it is desired to know how long the process has been in the soak mode, polling the processor and inputting "PRINT CST" would result in a printout of the time in seconds that the soak routine has been executing.

All the modules used to perform the digital control of the deposition process have been defined. In order to perform the statistical analysis exactly as that used in the monitoring phase, a separate support software package, Appendix C, was developed in the BASIC programming language. The package completes the analysis so that a basis now exists for comparison between the analog and digital controller.

TABLE I
DIGITAL CONTROLLER'S SOFTWARE MODULE
AND FUNCTIONS PERFORMED BY EACH

MAIN:	Sets Channel on Crossbar Scanner Encodes DMM to take Voltage Reading Writes Termination Message on Deposition Completion
KEYIN:	Interprets Commands from Teletype Prints Response to Teletype on Command
CKI:	Transfer Control to Proper Routine on Clock Interrupt
TRAP HANDLER:	Services Software Trap Instructions
RISE:	Calculates Rise Increment Steps D/A Each Second Passes Control to Soak Routine
SOAK:	Maintains D/A at Final Rise Value Counts Seconds for Execution Passes Control to Deposition Routine
DEPOS:	Obtains Freq Value Calculates Rate Value Calls APPASX Routine Compare D/A Value for Max/Min Assigns Multiplexer Channels Sets D/A Values Commands Punch Routines
APPASX:	Calculates Rate Error from Rate Value Calculates Controller Output
ADD:	Stores D/A Values Between Samples Sets Max/Min D/A Values
DACQ:	Controls Multiplex Values for DMM Command Measurements Converts BCD to 3 Word Flt. Pt.
CTLMDX:	Controls Multiplexer Status
POWER FAIL:	Stores Working Register on Power Loss Resets Hardware to Status Prior to Power Loss on Power Up Restores Working Registers on Power Up
DEBUG:	Conversational Interface with Machine Language Sets Sample Time

TABLE II
VARIABLE LIST FOR DIGITAL CONTROLLER SOFTWARE

Variable	Definition
Rate Set	Desired Rate Value
Rate	Current Rate During Execution
Initial Rise	Initial Rise Input Value
Final Rise	Final Rise Input Value
Rise Time	Rise Time Desired in Seconds
Soak Time	Soak Time Desired in Seconds
Deposit Time	Deposit Time Desired in Seconds
Thickness	Desired Termination Frequency
Max Power	Maximum Increment D/A Can Be Increased
Min Power	Minimum Increment D/A Can Be Decreased
B2	Velocity Term
Punch On	Activates Punch Routine
Deposit	Initiates DEPOS Routine
CRT	Current Rise Time
CST	Current Soak Time
CDT	Current Deposit Time
Go	Starts Controller Processing
X	Emergency Stops

Chapter 6

CONTROLLER OPTIMIZATION

Experiments were performed holding the velocity multiplier, W , at a constant value while varying the sample time of the controller. These experiments demonstrated not only a sensitivity of the controller to the variation of the velocity multiplier, but also to sample time variations. A series of experiments to step each of the variables were conducted in order to establish the optimal velocity multiplier and sample time for the digital controller. The matrix of deposition runs used to systematically evaluate the variables is illustrated in Fig. 6.1. For each material, the matrix is executed for the common deposition rates of one, five, and ten Hertz/sec. It is quite evident that the number of test runs, forty-five for the three rates, would become quite enormous if a large number of materials were investigated.

Based on the need to have a digital controller capable of depositing a wide range of materials, two materials, silver and tin selenide, each having widely different deposition characteristics were used. Thus, a total of ninety deposition runs, assuming one run per matrix point, had to be made to gather sufficient data to allow determination of the parameter values needed for optimal performance.

The basis of comparison for the parameters was the statistical analysis routine presented in Chapter 3. The validity of a single

Velocity Mult. Sample Time					
	1	2	3	4	5
1	X	X	X	X	X
4	X	X	X	X	X
7	X	X	X	X	X

Figure 6.1. Variable Matrix For Digital Deposition Controller

run per matrix point seems questionable as a basis for comparison. If for a particular matrix point the statistical parameters indicate a given value, was the value due to a system perturbation of the affect of the matrix parameters? In order to answer the question, multiple runs per matrix point were included in the test sequence. Then the statistical mean of the parameter for multiple runs gave good indications of the performance of the matrix point.

The next concern was the determination of the number of runs per matrix point needed to have confidence that the statistical analysis does represent a true value. Ideally, a large number of runs, per matrix point, would give an adequate indication of the matrix value but would be impractical. It can be assumed that, for a large number of experiments, the statistical parameters, i.e., mean rate and standard deviation, can be represented by a normal distribution or in the case of a small number of samples approximated by the t-distribution. The second assumption to consider is that a ninety percent (90%) confidence interval for the true value of the statistical parameters can be adequately defined based on the data taken.

Hayslett [14] established a technique to determine the interval in which the true statistical parameter was bounded. In order to calculate the upper and lower range in which the true value of the statistical parameter can be expected to be found, the following relationship is to be used:

$$\mu_u = \bar{x} + t_{\alpha/2}(*s/\sqrt{n}) \quad (6.1)$$

and

$$\mu_L = \bar{x} - t_{\alpha/2}(*s/\sqrt{n}) \quad (6.2)$$

Where μ_u = the upper confidence limit,

μ_L = the lower confidence limit,

\bar{x} = the measured mean value of the sampled data,

$t_{\alpha/2}$ = the t-distribution for given confidence level,

α = (1-confidence level),

s = the measured standard deviation of the sample data, and

n = the sample number.

Initially, estimations for a sample size indicated that three samples per matrix point might suffice as a true indication of statistical measure. Using the standard deviation of the rate data about the statistical mean as the parameter of interest, several matrix points were run for each of three chosen rates. Table III shows the results along with the interval in which the true standard deviation would be contained. As can be seen, the values of the interval appear to be close to the measured value. Thus, the choice of three samples per matrix point was accepted as sufficient.

With the criterion established that three or more samples would suffice to describe a matrix point, a set of data containing two hundred and forty (240) seconds was taken for each matrix point at each of the desired rates for both silver and tin selenide. A time interval of two hundred and forty seconds was chosen as a satisfactory control interval for two reasons: (1) the matrix size restriction in the support software and (2) the adequacy of the information gathered.

As indicated in Chapter 5, support software to plot and analyze the data acquired during the process control was written in BASIC. Ease of data manipulation made it advantageous to input all the data into the processor and let the routine call for it when desired. BASIC has a

TABLE III

SAMPLE OF RUNS TO SHOW INDICATION TRUE STATISTICAL PARAMETER

Rate	Velocity Multiplier	Sample Time	Mean of Parameter	Standard Deviation of Parameter	Interval ± Mean
1	4	1	.21	.04	.07
5	2	4	.37	.02	.03
10	4	1	.51	.11	.19
10	2	4	.60	.05	.08
10	2	7	1.04	.02	.03
5	3	1	.47	.02	.04

maximum matrix size restriction of 256 elements, thus the matrix size restrictions. Since the analog controller had always been able to establish control within four minutes, 240 seconds, it was felt that if the digital controller was to be an improvement over the analog controller, it should also be able to gain control within four minutes. Thus, the justification for the 240 seconds time interval for each run.

Since statistical data, especially the mean and the standard deviation, have meaning only if the sampled data can be considered to be random and can vary as a normal distribution, Appendix E demonstrates that the rate variable data do satisfy these criterion. Having also shown that three or more samples per matrix are sufficient to define the influence of that point on the controller's sensitivity, the test runs for the matrix points were completed. The statistical standard deviation parameter for the several runs at each matrix point has to be "massaged" to obtain the average and the standard deviation. The standard deviation of the rate data was chosen as the parameter of interest for evaluation because it gave the best measuring tool.

Averaging the several runs at each matrix point and recording the results, a completed matrix for a given material and rate, as shown in Fig. 6.2, can be obtained for analysis. To circumvent the numerical analysis task involved with the six separate matrices of fifteen points each, the data were plotted in a series of graphs, Appendix E. This permitted a quick analysis and a choice of optimum variables to be made. From an investigation of the graph, Fig. 6.3, a trend can be deduced for the material. As shown in the figure, the value of the mean of the standard deviation appeared to be the lowest for a velocity multiplier of four for all sample times. Analysis of the other data in Appendix F

Velocity Mult. Sample Time					
	1	2	3	4	5
1	1.16	1.38	.81	.34	.80
4	1.14	.70	1.36	.44	.60
7	1.56	.54	.64	.58	.53

Figure 6.2. Variable Matrix for Digital Controlling a Silver Deposition at a Rate of Ten Hertz/Sec

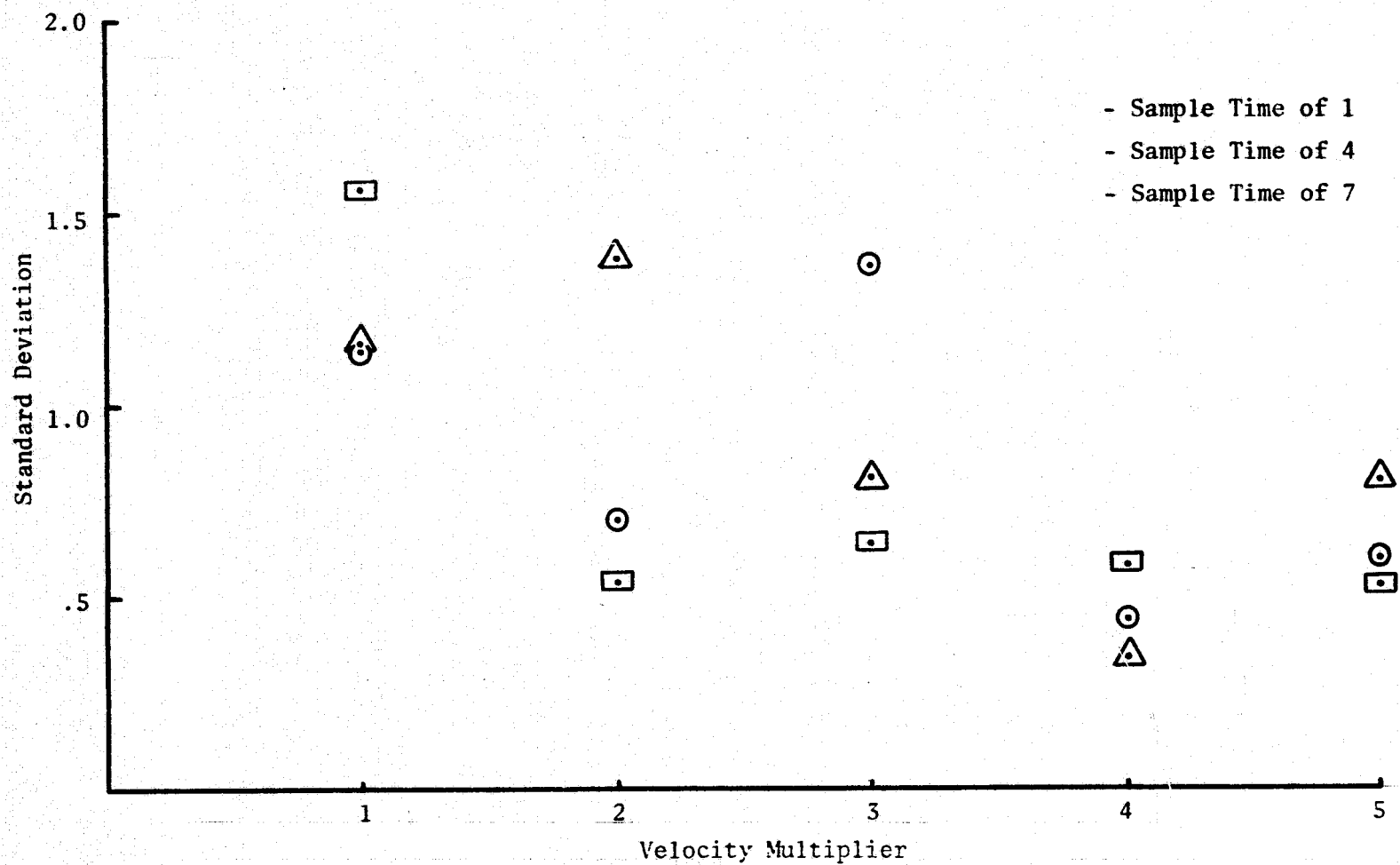


Figure 6.3. Standard Deviation versus Velocity Multiplier for Silver Deposition at Ten Hertz/Sec

yielded similar results. Thus, the conclusion was reached that a velocity multiplier of four appeared to give an optimal controller response. Further analysis of the data led to the conclusion that the choice of the sample time was not as straightforward as the choice of the velocity multiplier. For the data shown in the figure, it would appear that a sample time of one second would be the optimal choice. However, in order to obtain a set of parameters for each material, independent of the rate, all the rate data had to be investigated.

For silver, the data for the lower rates indicated a sample time of four seconds yielded the best result. Examining the individual deposition plots for the two sample times in question, a decision to choose the sample time of four seconds was made. Conducting a similar analysis for tin selenide yielded a result of a one second sample time for optimal response.

Table IV indicates the final results of the experimental testing which gave values for the unknown parameters established in Chapter 4. Using the results of the table, a series of twenty-five runs per rate per material was made in order to evaluate the optimal digital controller versus the analog controller.

This chapter has established the tuning procedure used to obtain the values of the unknown variables in the controller equations. In the following chapter, the analysis of the chosen controller for each material will be conducted.

TABLE IV
PARAMETER VALUES FOR THE OPTIMAL DIGITAL CONTROLLER

	Velocity Multiplier	Sample Time
Silver	4	4
Tin Selenide	4	1

Chapter 7

ANALYSIS OF OPTIMIZED DIGITAL CONTROLLER

This chapter will analyze the results achieved with the optimized digital controller and compare it with the optimized analog controller. Using the sample times and velocity multipliers established in Chapter 6 for silver and tin selenide, a series of twenty-five depositions at the most common rates were made. A similar series of depositions were conducted with the analog controller in order to obtain a basis for comparison.

A statistical analysis of each of the deposition runs yielded a mean rate value and a standard deviation about the mean. A statistical analysis of the mean rate values for the series of depositions yielded a mean expected rate value, \bar{R} , and a standard deviation about this mean, $S_{\bar{R}}$. Similarly, an analysis of the standard deviation of the rate variable about the mean for each run in a series resulted in a mean value for the standard deviation, \overline{SD} , and a standard deviation about this mean, $S_{\overline{SD}}$. Table V illustrates the results for both the digital and analog controller for the two materials at the common rates. It is advantageous to plot the data in Table V, to better illustrate the contrast between the two controllers. By normalizing the mean about the zero axis and the peak of the normal distribution function to one, the data can be collectively illustrated as a function of \overline{SD} .

TABLE V
RESULTS OF DIGITAL/ANALOG CONTROLLERS AT OPTIMAL SETTING

Material	Controller	Commanded Rate (Hz/sec)	Mean Rate (\bar{R})	Stand. Deviation of Mean Rate ($S_{\bar{R}}$)	Mean Stand. Deviation (\bar{SD})	Stand.Deviation of \bar{SD} ($S_{\bar{SD}}$)
Silver	Digital	5	4.49	.10	.47	.15
Silver	Digital	10	9.58	.28	.43	.09
Silver	Analog	10	14.25	.20	1.73	1.74
Tin Selenide	Digital	5	4.48	.04	.35	.09
Tin Selenide	Digital	10	9.46	.09	.56	.11
Tin Selenide	Analog	5	4.65	.56	2.33	1.22
Tin Selenide	Analog	10	8.31	.70	1.96	.85

Setting the mean, μ , to zero and the standard deviation, σ , to the various values for \overline{SD} , a normal distribution function, $f(x)$, using (7.1) can be calculated as the mean rate is varied from the zero axis.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-1/2\left(\frac{\mu-x}{\sigma}\right)^2} \quad (7.1)$$

$f(x)$ = distribution of the rate values about the mean

μ = mean rate

σ = standard deviation

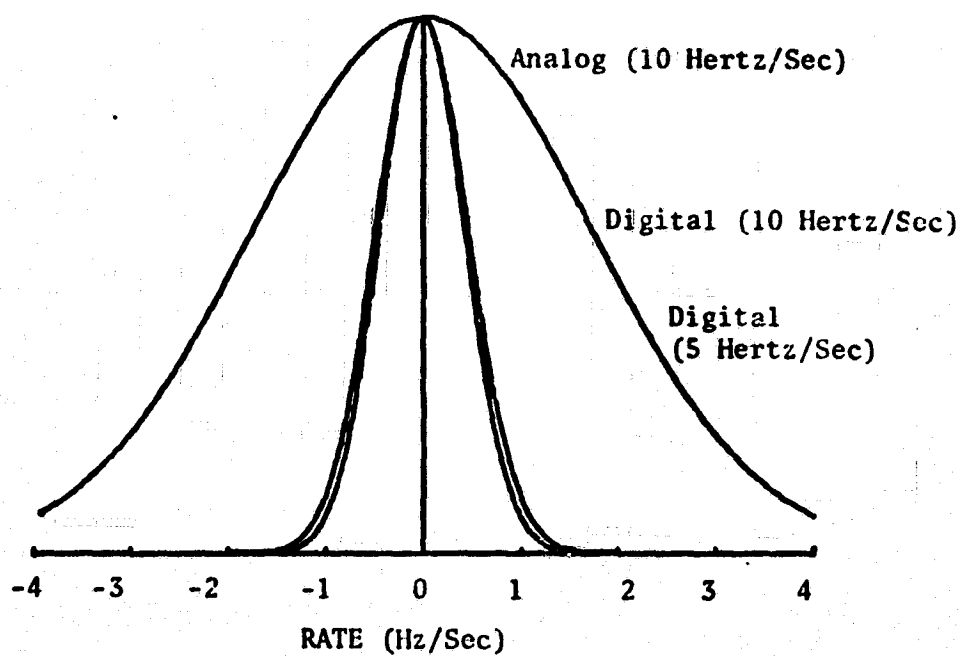
Normalizing the peaks of the distribution functions to one, a series of graphs, Fig. 7.1, which illustrates the distribution of the deposition rate variable about the mean can be generated.

As an example, the \overline{SD} for silver deposited at a rate of 10 Hz/sec is .43 with a mean of 9.58 Hz/sec. This indicates that the deposition rate variable can be expected to be within an interval of .215 Hz/sec about the mean. Thus a relative measure of the effectiveness of the controller can be seen.

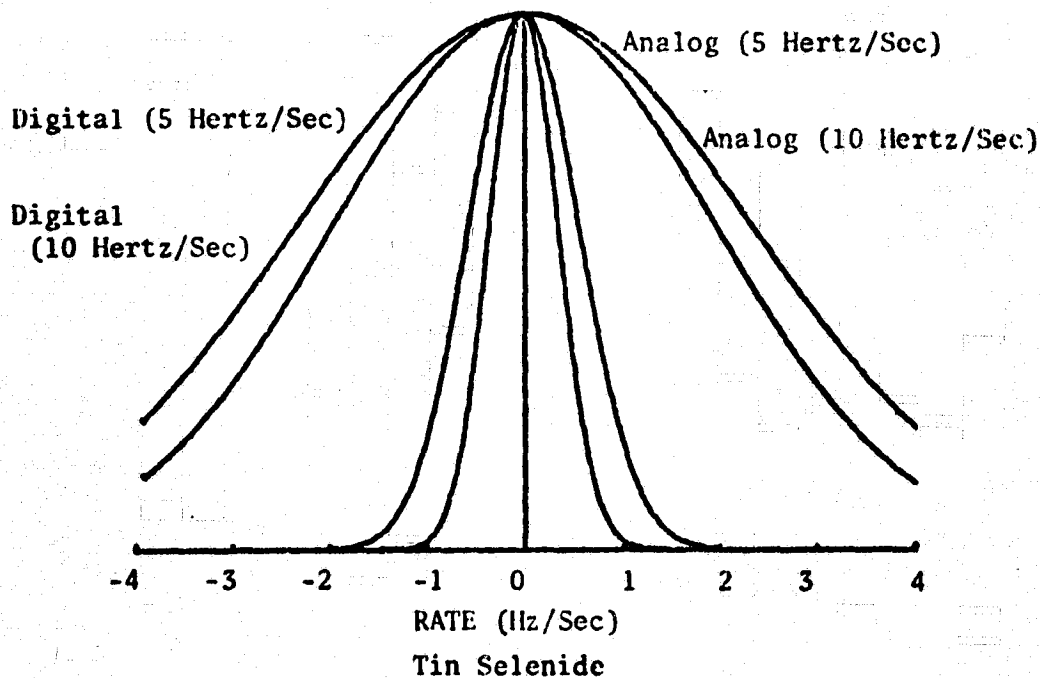
As seen, a marked improvement over the analog controller can be expected from the digital controller. The expected standard deviation about the desired mean is quite small for the digital controller as compared to that for the analog controller.

Using Table V and (7.2) an indication of the controllability for the digital controller can be defined for a given material at a given rate.

$$CF \equiv \overline{SD}/2 \quad (7.2)$$



Silver



Tin Selenide

Figure 7.1. Normalized Distribution Curves for Silver/Tin Selenide Deposition with Optimized Digital Controller

Thus, the controllability factor, CF, is the interval spanned by one half the mean value of the standard deviation. For example, at a deposition rate of 10 Hz/sec the table yields an expected standard deviation of .43 Hz/sec and a CF of .215 for silver. Thus, the actual deposition rate variable could be expected to vary from 9.79 Hz/sec to 10.21 Hz/sec for a commanded rate of 10 Hz/sec. This translates to a deposition rate between 1.10 \AA/sec and 1.15 \AA/sec or a controllability factor of approximately $.024 \text{ \AA/sec}$ control. Similar analysis for the tin selenide yields a controllability for the digital controller of approximately $.1 \text{ \AA/sec}$.

A measure of reproducibility for thin film devices produced with the digital controller can also be projected from Table V. From the information in the table, a numerical indication of the reproducibility factor, RF, for a given material and rate can be calculated using

$$RF = 3(S_{\bar{R}} + S_{\overline{SD}}) + \overline{SD}. \quad (7.3)$$

The factor of three in (7.3) represents three standard deviations which assure the spread needed to cover the majority of deposition rates.

This relationship can best be illustrated by the graph in Fig. 7.2. For any deposition run the mean rate is defined to be \bar{R} . Three times $S_{\bar{R}}$ gives the interval within which the mean rate is expected to be contained. Assuming that the mean rate occurred at either end of the interval, the mean standard deviation (\overline{SD}) will give the interval on either side of the mean rate about which the actual rate variable can be expected to fluctuate. Three times $S_{\overline{SD}}$ will include the total interval in which the deposition rate variable should be found. Thus, the deposition rate variable should always be found within the limits

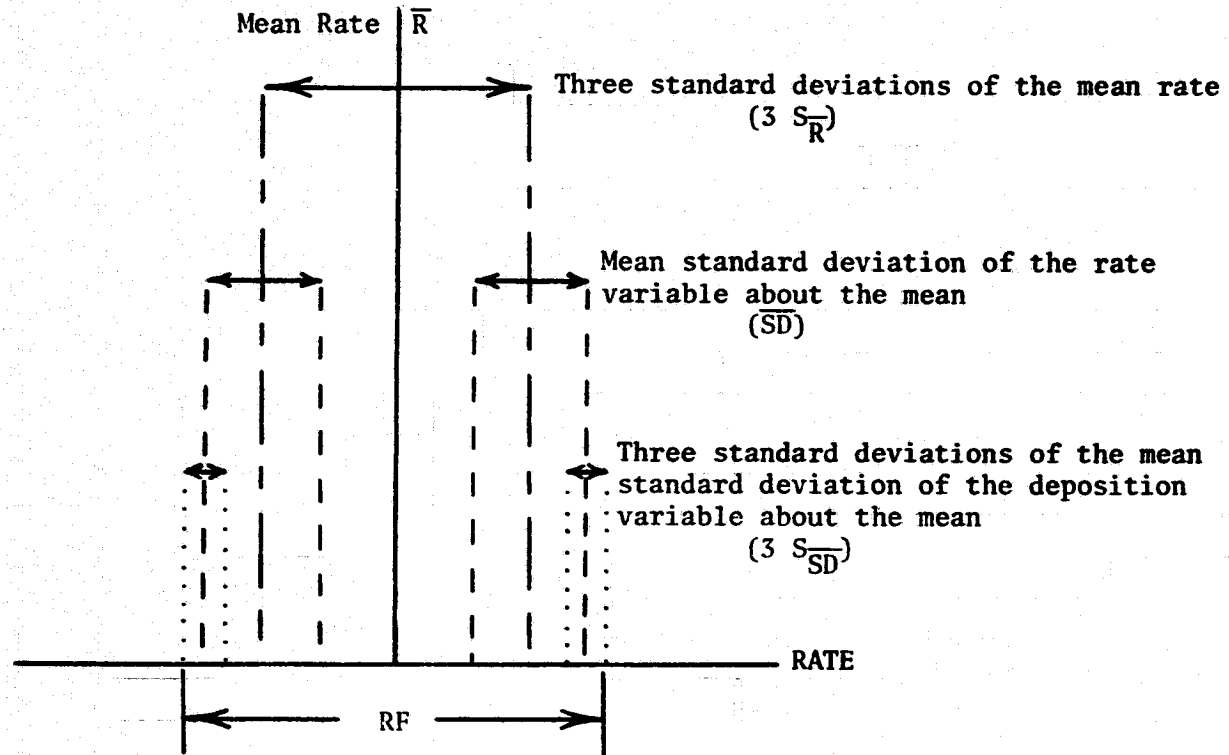


Figure 7.2. Graphical Illustration of the Reproducibility Factor for a Thin Film Deposition Controller

established by the reproducibility factor and over which the smaller the value RF, the smaller the interval the deposition rate variable should fluctuate.

Table VI illustrates both the controllability factors and the reproducibility factors measured with the analog and digital deposition controllers. As can be seen, the digital controller demonstrated superior results for both factors. To illustrate the response contrast of the analog and digital controllers, Fig. 7.3 depicts a deposition controlled by the analog controller and a digitally controlled deposition for the same material and rate. Shown in the figure, the digital controller achieves steady state response faster and with less overshoot than the analog controller.

To better illustrate typical responses of the digital controller, Fig. 7.4 shows a deposition run for both tin selenide and silver. As shown, both responses had achieved steady state in less than 45 seconds after the start of the deposition. It can be seen that the silver deposition had a slight overshoot. This can be attributed to two factors. One, the initial higher control setting was held longer than optimally required due to the longer sample time. Secondly, the lower than desired controller output at the completion of the soak phase resulted in a larger turn on power to achieve a rate. If the output at the completion of the soak phase had been nearest the power setting required to achieve the desired rate, the overshoot experienced with the longer sample time would have been minimal.

The longer sample time does offer an advantage in that part of the noise measured in the rate signal is filtered out. Thus, smaller changes are applied to the controller output. This response

TABLE VI

**CONTROLLABILITY AND REPRODUCIBILITY FACTOR FOR DIGITAL/ANALOG
CONTROLLERS AT OPTIMAL SETTINGS**

Material	Controller	Commanded Rate (Hz/sec)	Controllability Factor (CF) (Hz/sec)	Reproducibility Factor (RF) (Hz/sec)
Silver	Digital	5	.24	1.22
Silver	Digital	10	.22	1.54
Silver	Analog	10	.87	7.55
Tin Selenide	Digital	5	.18	.74
Tin Selenide	Digital	10	.28	1.16
Tin Selenide	Analog	5	1.17	7.67
Tin Selenide	Analog	10	.98	6.61

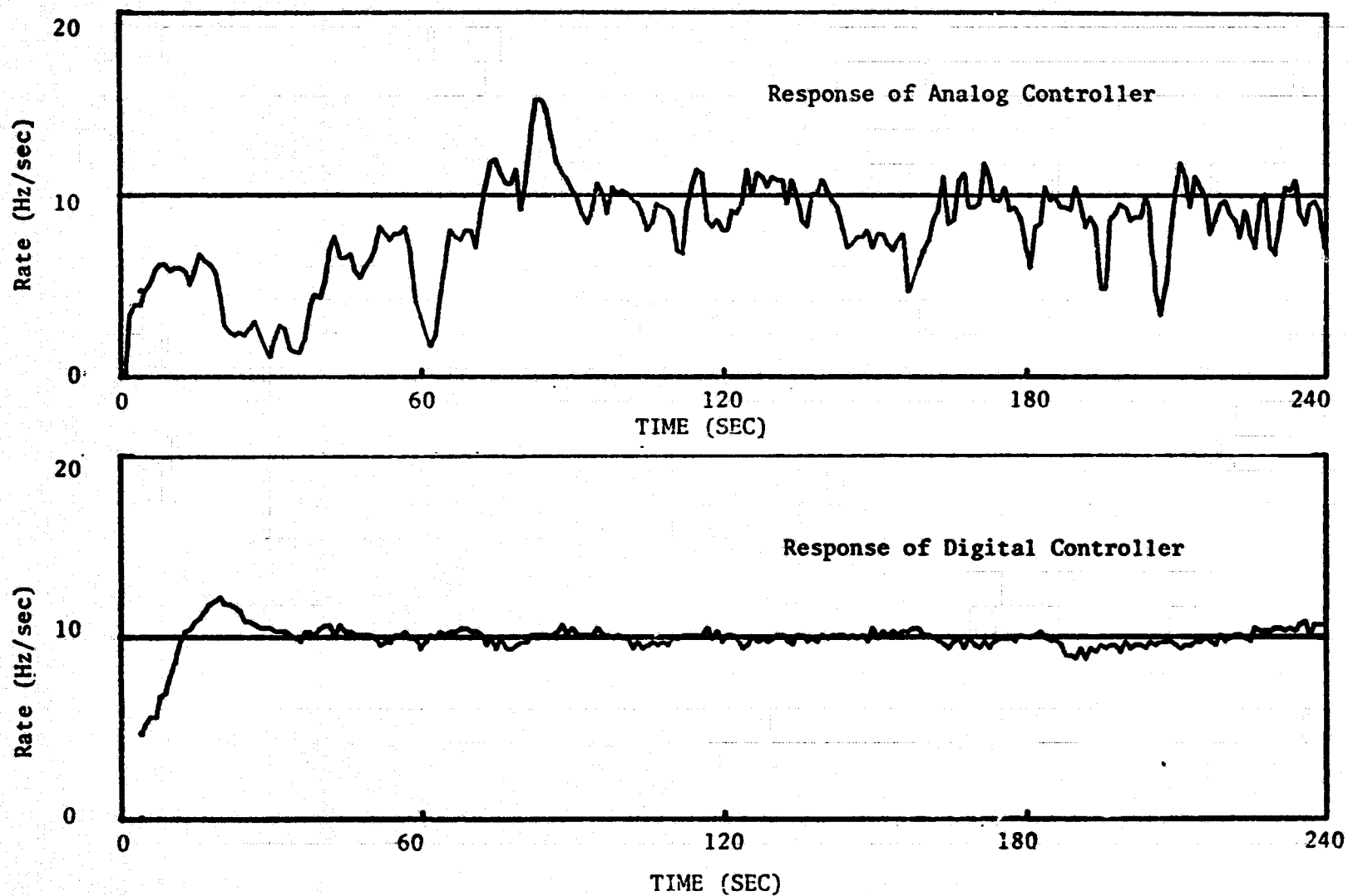


Figure 7.3. Analog-versus-Digital Controller Responses For Tin Selenide at a Deposition Rate of 10 Hz/sec

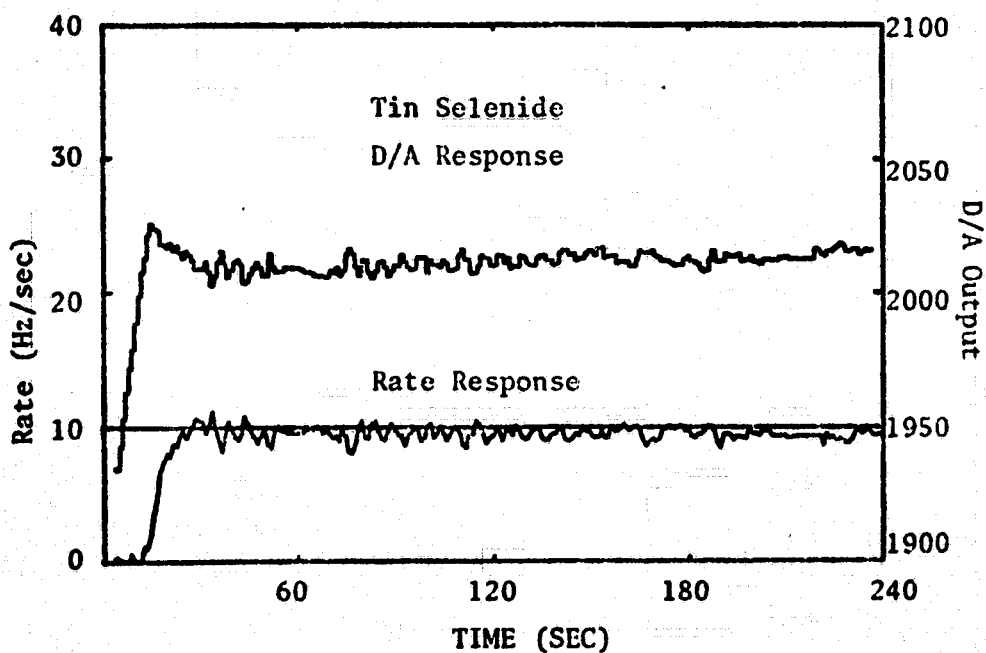
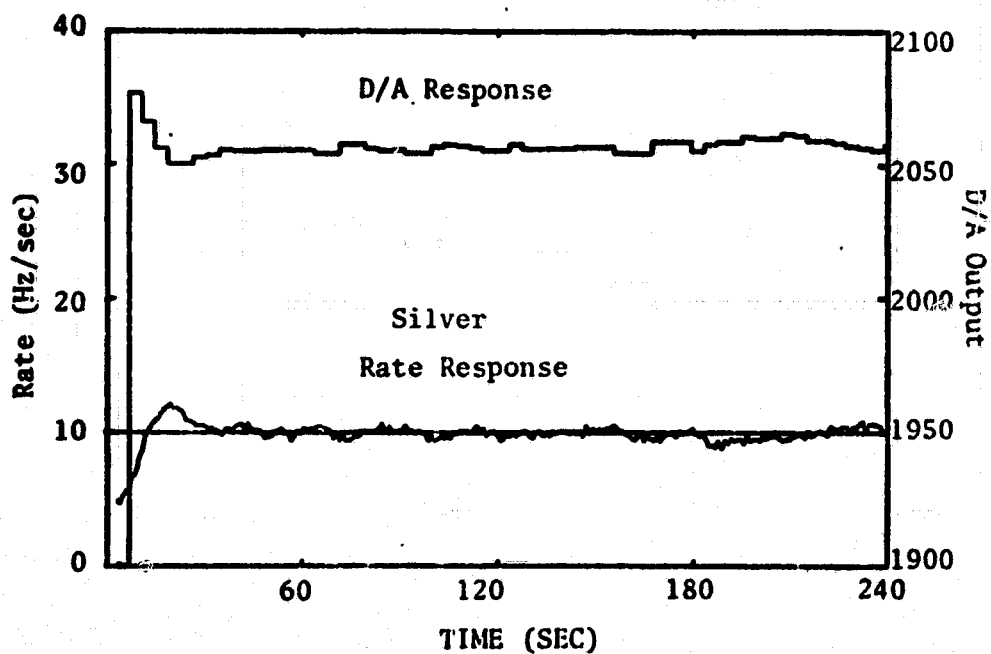


Figure 7.4. Typical Digitally Controlled Depositions

characteristic is also useful when a crystal snap occurs as will be introduced later in the chapter.

The shorter sample time used for the tin selenide resulted in minimal overshoot due to the rapid monitoring and updating of the controller output. As seen, the controller output peaked and began to cut back on the output before the rate response achieved the desired level. This illustrated the lead phase property or the desired anticipation of the controller to the response of the rate.

Illustrating the controller's dynamic capability, Fig. 7.5 shows the responses achieved with the digital controller for both tin selenide and silver during a deposition process containing the three rates of one, five, and ten Hz/sec, respectively. Observing that for silver and relative overshoots at the change of the rates are not as great as the initial overshoot, the effect of the power setting at the beginning of the process can be illustrated.

The overshoot problem can be reduced by either of two techniques. One, a software modification that slowly brings the soak power setting to a level that initiates a slow rise and then reduces the power. Second, a hardware modification could be made so as to locate the crystal detector under a shutter mechanism. This would shield the device until a steady rate had been attained.

Figure 7.6 illustrates the manner in which the digital controller reacts to a crystal snap. Many times the snap is not even sensed, especially on the longer sample times, due to the snap occurring between samples. Even if the controller senses the snap, the minimum limiter setting for the controller output eliminates the electron gun being turned completely off as was the case in the example shown in Fig. 1.1.

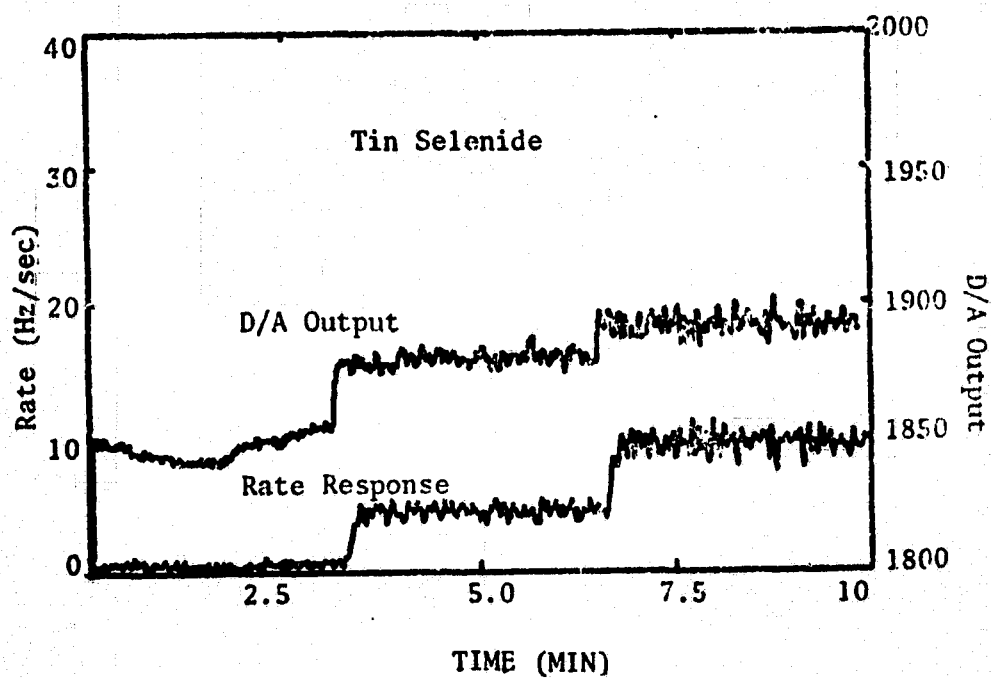
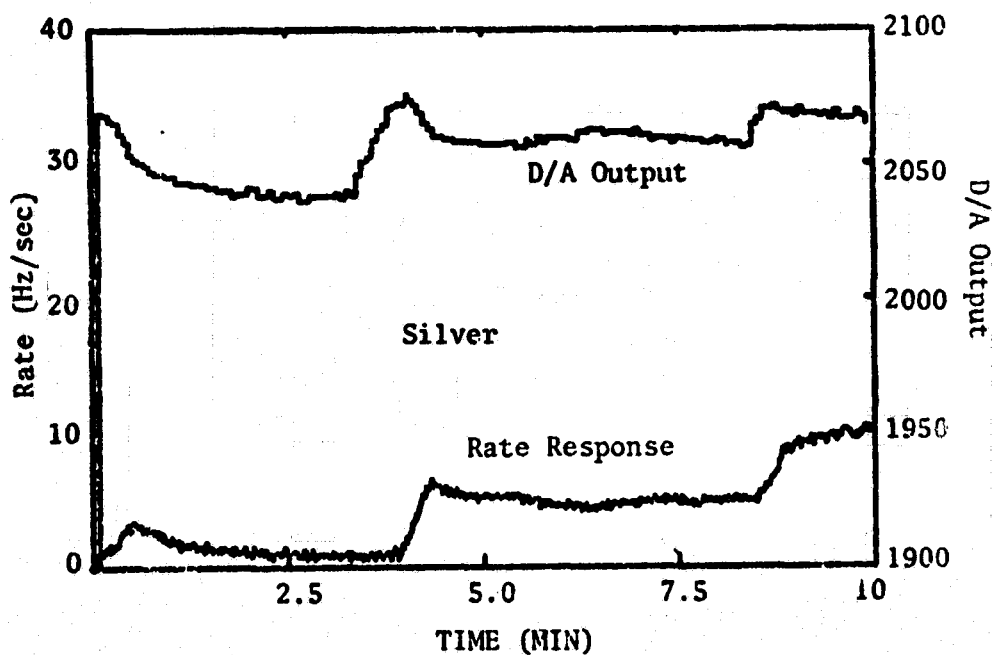


Figure 7.5. Dynamic Response Capability of Digital Controller

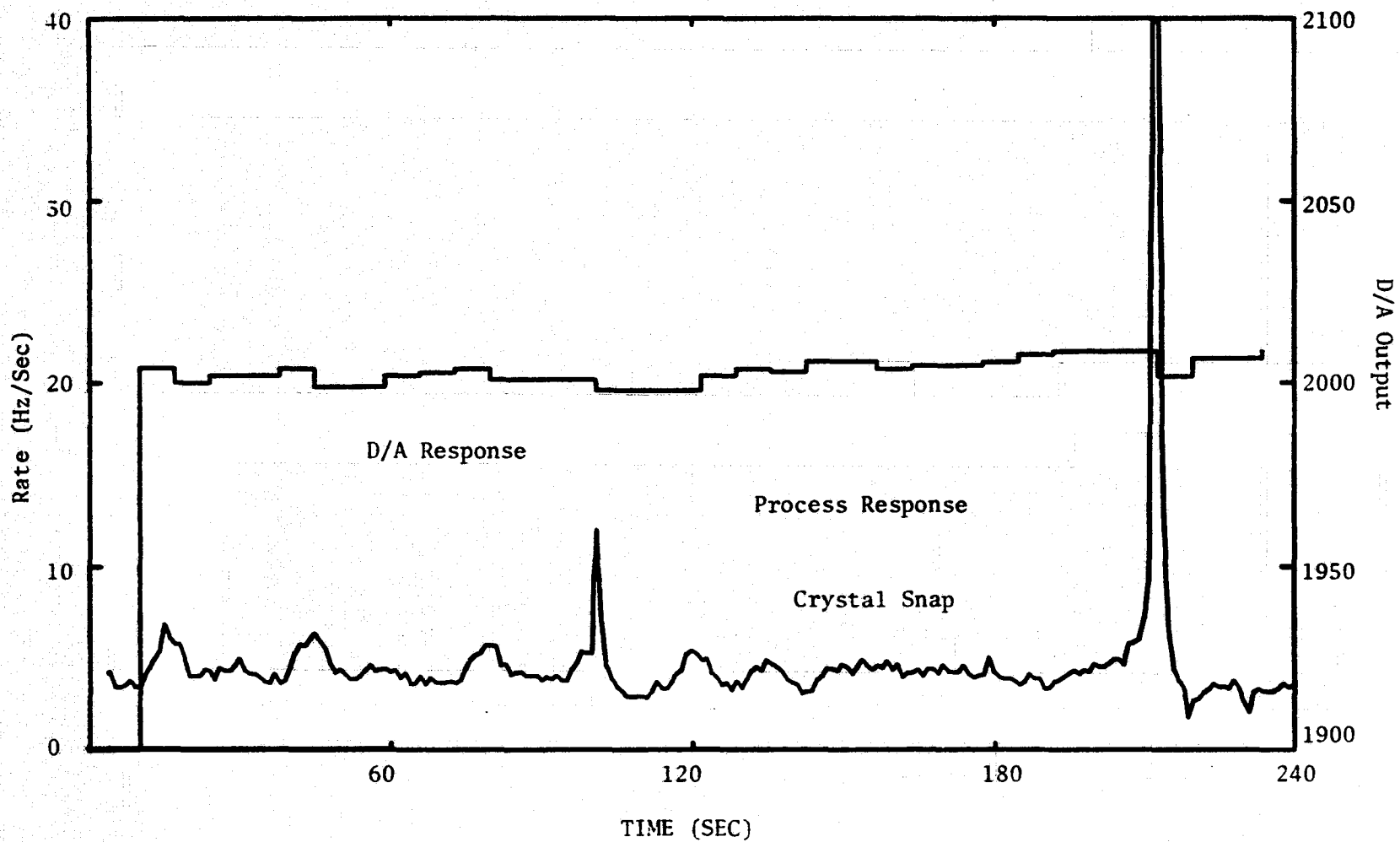


Figure 7.6. Illustration of Crystal Snap Response of Digital Controller

When the digital controller does sense the snap, the recovery time is seconds as compared to the forty-five seconds or more experienced with the analog controller. Not only is the effect on the controller output minimum, the overall effect to the rate of deposition is held to a minimum. As illustrated in Fig. 1.1, the rate went to near zero. When it did come back up, the overshoots and transient were enough to possibly effect the characteristics of the device being manufactured. Thus, it is desirable to have the snaps filtered out and their effect held to a minimal during the fabrication of the thin film devices.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

This dissertation has described a digital controller that controls the thin film deposition rate parameter. This chapter will summarize the conclusions of the effort and suggest recommendations for future work that might improve the system further.

A design criteria for a digital control system along with the hardware and software requirements has been described in this dissertation. A comparative analysis of data gathered using both the analog and digital controller has resulted in the conclusion that the digital deposition rate controller offers many advantages over the analog rate controller. To sum up these advantages, Table VII gives a composite comparison of the two controllers. It might be noted that some of the parameters in the table are expressed in terms of $\text{\AA}/\text{sec}^2$ versus the Hz/sec previously defined. The values were obtained by using the conversion factor obtained in Chapter 3. The purpose of changing units was to contrast between the materials and the controllers and to establish continuity between the control terminology and the physical terminology.

The completion of the task has resulted in a digital thin film deposition controller whose characteristics exceed those of any known deposition controllers on the commercial market. A control method has been developed that allows the researcher to concentrate on the effect

TABLE VII
COMPARISON OF DIGITAL VERSUS ANALOG
THIN FILM DEPOSITION CONTROLLERS

	Digital	Analog
Rise Time	65000 sec	180 sec
Soak Time	65000 sec	180 sec
Response Time to Steady State	< 45 sec	≈60 sec
Recovery from Crystal Snap	< 10 sec	*45 sec
Controllability Factor	.02 Å/sec ² * (.05 Å/sec ²)**	.1 Å/sec ² (.2 Å/sec ²)
Reproducibility Factor (Total Rate Spread)	.17 Å/sec ² * (.23 Å/sec ²)**	.9 Å/sec ² (1.29 Å/sec ²)
Mean Standard Deviation about the Desired Rate	.05 Å/sec ² * (.11 Å/sec ²)**	.2 Å/sec ² (.38 Å/sec ²)
Deposition Termination Factor	Time/Thickness	Thickness
Permanent Record of Deposition Parameter (PLOTS)	Yes	No
Statistical Analysis of Deposition Parameters	Yes	No
Deposition Parameter Data in Permanent Format (Paper Tape)	Yes	No
Deposition Parameter Input Format	TTY (conversational)	Interactive-Potentiometers
Ability to Real Time Monitor Control Parameters (Rise Time, Soak Time, Deposition Time, etc.)	Yes	No

* Parameter values for silver at a deposition rate of 1.0 Å/sec

** Parameter Values for tin selenide at a deposition rate of 2.0 Å/sec

of parameters other than rate control on device characteristics. Thus, the objectives established in Chapter 1 have been met. It therefore appears that the use of a digital controller for thin film deposition should result in better thin film devices than could be obtained with an analog controller.

SUGGESTED FUTURE WORK

It is recommended that this work be continued by investigating the values of the sample time and velocity multipliers for other materials. Also, the investigation of using the control technique coupled with the work [15] to determine the possibility of reducing the hardware requirements is suggested.

Additional software routines to better achieve a soak power sufficiently close to the deposition power would enhance the capabilities of the controller software package. The incorporation of the routines to allow real time plotting of rate data along with statistical analysis would also be desirable improvements to the software package.

Hardware modification to include a processor controlled shutter between the crystal detector and the substrate would improve the system. This would allow filtering the initial transients and achieving steady state before opening the shutter. In a similar manner, the processor could close the shutter at the termination of a deposition. Thus, insuring that residual evaporation would not affect the thin film device being fabricated.

Augmentation of the system with another D/A and proper set of software to control the switching process could result in a system capable not only of co-deposition but also make possible the control of

depositions in two separate vacuum chambers. Further modification of the software could result in a package to separately control two vacuum depositions independently while using a common set of software.

Ultimately, an interactive software routine coupled with the BASIC conversational language could be developed which operated as a time sharing between the deposition process while performing user requested calculations.

REFERENCES

REFERENCES

1. Abraham, F. F. and G. M. White, "Computer Simulation of Vapor Deposition on Two Dimensional Lattices," Journal of Applied Physics, 40, 4, (March 15, 1970), 1841-1849.
2. Chopra, K. L. and M. R. Randlett, "Modular Electron Beam Source for Thin Film Deposition," Solid State Electronics, 1421-1422, September.
3. Turner, J. A., "Deposition Monitoring and Control," Chap. 7, Sect. b, Handbook of Thin Film Technology, McGraw-Hill Book Comp., New York, NY, 1970.
4. Butuzan, R., "Deposition Monitoring and Control," Chap. 7, Sect. e, Handbook of Thin Film Technology, McGraw-Hill Book Comp., New York, NY, 1970.
5. Weissman, J. and A. Hirsch, "An Electromechanical Device for Measuring the Deposition Rates of Thin Films," Vacuum, 19, 12, (June 1967), 579-581.
6. Brownell, R. B., W. D. McLennan, R. L. Ramey, and E. J. White, "Automatic Thin Film Vacuum Deposition System of High Stability," The Review of Scientific Instruments, 35, 9, (September 1964), 1147-1150.
7. Lins, S. J. and R. E. Oberg, "Latest Thing in Thin Film Automatic Deposition Control," Electronics, (March 29, 1963).
8. Lawson, W. H., "A Versatile Thin Film Thickness Monitor of High Accuracy," Journal of Scientific Instruments, 44, 1967, 917-921.
9. Fair, R. B., "Analysis and Design of Ion Beam Deposition Apparatus," Journal of Applied Physics, 42, 8, (July 1971), 3176-3181.
10. Riegert, R. P., "Optimum Usage of Quartz-Crystal Monitor-Based Devices," Proc. of Fourth International Vacuum Congress, 1968, 527-530.
11. Effron M. S., C. H. Farrow, and F. R. Titcomb, "Thin Film Manufacturing by Computer Control," Journal of Vacuum Science Technology, 10, 1, (January/February 1973), 80-82.

12. Centner, R. M. and R. A. Wilson, "Computer Control of Vacuum Deposition Processes," 1970 WESCON Technical Papers, IV, 1970, 122-125.
13. Kalman, R. E., "Design of a Self-Optimizing Control System," Transactions of the ASME, (February 1958), 468-476.
14. Hayslett, H. T., "Confidence Limits," Chap. 10, Statistics Made Simple, Doubleday & Comp., Garden City, NY, 1968.
15. Turner, D. T., "The Design of a System for Codeposition of Semiconductor Thin Films," Master Thesis, Tennessee Technological University, 1975.
16. Butuzou, U. S., B. S. Danilin, and M. N. Kuznetsou, "Set of Equipment for Controlling a Thin Film Thermal Deposition Process," Automatika i Telemekhanika, 8, (August 1969), 190-194.
17. Sugata, E. and M. Nagata, "Computer Controlled Vacuum Deposition System by Electron Beam Heating," Electronics, (June 15, 1969), 167-172.
18. English, J., T. Putner, and L. Holland, "Programmed Control of Vacuum-deposited Multilayers," Proceedings of the Fourth International Vacuum Congress, 1968, 491-495.
19. L'vov, V. A., V. A. Sterelyukhim, and E. I. Cherepov, "Computerized Control of Deposition of Films with Given Thickness," Vychislitel'nye Sistemy, 35, 1969, 122-125.

APPENDICES

APPENDIX A

The following computer program written in BASIC was used to conduct the monitoring phase of the research effort. This program has the capability of monitoring the deposition parameters at one second intervals during a deposition run under analog control. At the end of the monitoring mode, the software is capable of plotting the SCR and deposition rate parameters, conducting a statistical analysis on rate data, printing a label for the plot with pertinent deposition information, or punching the data on the High Speed Punch for permanent paper tape storage.

```

01 REM PROGRAM TO MONITOR & DATA ANALYSIS FROM DEPOSITION
02 REM OPTIONS REQUIRED -- 2,H,R,S,X,1,F,Q,T
03 REM...REVISED: OCTOBER 31,1973
04 GOTO 10
05 FOR N8=1 TO G0
06 LETU=EXF(17);LET U=EXF(11,N8+G0,2,7,21)
07 LET U=EXF(11,N8,2,4,20);LET U=EXF(20,1,N8)
08 NEXT N8
09 PRINT "":GOTO 30
10 PRINT "MAX # OF MEASUREMENTS";:INPUT G0
11 LET U=EXF(20,2,G0)
12 PRINT "FREQ METER - 3 OR 10 (KHZ)";:INPUT M2
13 PRINT "MIN,MAX RATE SCALES";:INPUT R1,R2
14 PRINT "MIN,MAX SCR SCALES";:INPUT S1,S2
15 IF M2=10 THEN 25
20 LET M=564.4567;LET B1=-5.40542;GOTO 30
25 LET M=1865.658;LET B1=-44.81548
30 REM
35 PRINT "OPERATION:"
36 PRINT "1-PLOT(SCR), 2-STAT. ANAL., 3-PUNCH,"
38 PRINT "6-PLOT(RATE), 7-STOP, 8-LABEL, 9-MONITOR"
41 LET N8=EXF(21,1);LET G0=EXF(21,2)
42 IF N8<>0 THEN 45
43 PRINT "INPUT ACTUAL # OF SAMPLES";:INPUT N8
44 LET U=EXF(20,1,N8)
45 INPUT Q9
47 IF Q9=9 THEN 900
48 IF Q9=8 THEN 500
50 IF Q9=7 THEN STOP
55 IF Q9=6 THEN 200
70 IF Q9=3 THEN 270
75 IF Q9=2 THEN 335
80 IF Q9=1 THEN 95
85 GOTO 30
95 PRINT "INSTALL BLUE PEN...THEN CR";:INPUT A9
100 LET P1=S1;LET P2=S2
105 IF EXF(23)=16 GOTO 105
110 LET U=EXF(28,0,1,550,S2,S1,1,1,600,0)
130 GOTO 250
200 PRINT "INSTALL BLACK PEN...THEN CR";:INPUT A9
205 LET P1=R1/M;LET P2=R2/M
210 IF EXF(23)=16 GOTO 210
215 LET U=EXF(28,1,551,1100,P2,P1,1,1,600,0)
250 GOTO 30
270 LET U=EXF(14,1,N8+G0)
275 GOTO 30
335 PRINT "INPUT MIN AND MAX POINTS";:INPUT M8,M9
340 LET M8=M8+G0;LET M9=M9+G0
343 LET X1=(EXF(16,M9)-EXF(16,M8))/(M9-M8)
345 LET X=EXF(22,M8,M9,X1)
350 LET X1=X1*M
355 LET X=X/(M9-M8-1)
360 PRINT:PRINT:PRINT

```

```

365 PRINT "ANALYSIS COVERED POINTS ";MB-G0;" TO ";M9-G0
370 PRINT "STATISTICAL MEAN IS ";X1
375 PRINT "STATISTICAL STANDARD DEVIATION IS ";M*(X)^.5
380 PRINT "STATISTICAL VARIANCE IS ";M*M*X
385 PRINT:PRINT:PRINT:PRINT
390 GOTO 30
500 PRINT "DATE OF DEPOSTION...M,D,Y,#";:INPUT M1,D1,Y1,N1
505 PRINT"TYPE MATERIAL..KEY 1-QUARTZ,2-SILVER";
506 PRINT ",3-TINSELENIDE"
510 INPUT A8
515 PRINT"TYPE CONTROL..KEY 1-COMPUTER,2-SLOAN UNIT";
516 INPUT C1
520 LET S8=2
525 FOR I=1 TO 10:PRINT:NEXT I
530 PRINT "TEST DATE..."M1;" "/"D1;" "/"Y1;"#";N1
535 PRINT "DEPOSITION MATERIAL..."
540 IF A8=1 THEN PRINT "QUARTZ"
545 IF A8=2 THEN PRINT "SILVER"
550 IF A8=3 THEN PRINT "TIN SELENIDE"
565 PRINT "DEPOSITON MADE IN ";
575 IF S8=2 THEN PRINT "VARIAN ";
585 PRINT "VACUUM SYSTEM"
595 PRINT "DEPOSITON CONTROLLED BY THE ";
600 IF C1=1 THEN PRINT "COMPUTER"
605 IF C1=2 THEN PRINT "SLOAN UNIT"
610 PRINT:PRINT"          SCALES"
615 PRINT "PEN COLOR","MIN","MAX","FCT"
620 FOR I=1 TO 48:PRINT "-";:NEXT I:PRINT
635 PRINT "    BLACK",R1,R2,"RATE"
638 PRINT "    BLUE",S1,S2,"SCR"
640 FOR I=1 TO 10:PRINT:NEXT I:GOTO 30
900 PRINT "<CR> WHEN READY TO MONITOR";:INPUT A9
905 GOTO 05

```


APPENDIX B

The following computer program modules written in Programmable Assembly Language (PAL) comprise the major portion of the software package to perform the digital controlling of the thin film deposition processing. The modules listed are coupled with other vendor supplied routines such as the Floating Point Math Package, Debug, and IOX. The software packages are presented in the following sequence with a brief synopsis of each routine at its beginning:

MAIN
KEYIN
CKI
TRPHNP
RISE
SOAK
DEPOS
APPASX
ADD
DACQ
CTLMDX
POWER FAIL

MAIN

Sets Channel on Crossbar Scanner

Encodes DMM to take Voltage Readings

Writes Termination Message on Deposition Completion

1		:
2		: MAIN PROGRAM
3		:
4		: REV: 8/5/73
5		:
6		
7		.GLOBL START
8		.GLOBL DAQSUP,SENCDE,DAQEVL
9		.GLOBL FUNC,RANGE,CHAN,DACQ1,DACQ2,DACQ3,DACQ4
10		.GLOBL CTLMGX
11		.GLOBL CPFLAG,DTHFLG
12		.GLOBL C.X
13	000000	.CSECT
14		
15		: REGISTER ASSIGNMENTS
16		
17	000000	R0 = %0
18	000001	R1 = %1
19	000002	R2 = %2
20	000003	R3 = %3
21	000004	R4 = %4
22	000005	R5 = %5
23	000006	SP = %6
24	000007	PC = %7
25		
26	177776	PS = 177776
27		
28		: IOX COMMAND CODES
29		
30	000001	INIC = 1
31	000002	RESEC = 2
32	000003	RSTRC = 3
33	000004	WAITC = 4
34	000005	SEEC = 5
35	000011	REAC = 11
36	000012	WRIC = 12

37	000013	REARC	=	13
38	000014	WRIRC	=	14
39				
40		: IOX CALLS		
41				
42	000004	INIT	=	10T
43	000004	RESETIOX	=	10T
44	000004	RSTRT	=	10T
45	000004	WAITR	=	10T
46	000004	SEEK	=	10T
47	000004	READ	=	10T
48	000004	WRITE	=	10T
49	000004	READR	=	10T
50	000004	WRITR	=	10T
51				
52	000000	DEV0	=	0
53	177520	CKSR	=	177520
54	177520	MDXCTL	=	177520
55	177522	DMOUT	=	177522
56				
57	000000	KBD	=	0
58	000001	TTY	=	1
59	000002	HCR	=	2
60	000003	HSP	=	3
61				
62	104401	KEYIN	=	TRAP+1
63	104400	IOWAIT	=	TRAP
64				
65	000340	PRI07	=	340
66	000015	CR	=	015
67	000012	LF	=	012


```

1 000000 000000 000000
2 000001 000002
3 000006 000004
4 000010 000025
5
6 000012 016706 177762
7 000016 005037 177776
8 000022 000004
9 000024 000000
10 000026 002 000
11 000030 000001
12 000032 000300
13 000034 001 003
14 000036 012737 000004 177520
15 000044 012737 000003 177522
16 000052 004767 000000G
17 000056 016767 177726 000000G
18 000064 016767 177716 000000G
19 000072 016767 177706 000000G
20 000100 004767 000000G
21 000104 016767 000000G 000000G
22 000112 016767 000000G 000000G
23 000120 004767 000000G
24 000124 004767 000000G
25 000130 004567 000000G
26 000134 010000
27 000136 052737 000100 177520
28 000144 052737 000340 177776
29 000152 005767 000000G
30 000156 001407
31 000160 005067 000000G
32 000164 042737 000340 177776
33 000170 104401
34 000174 000763
35 000176 005767 000000G
36 000200 001407

```

```

LIM: .LIMIT
FUN: .WORD 2 ;VOLTAGE FUNCTION
RNG: .WORD 4 ;AUTO RANGE
CHNL: .WORD 21 ;CHANNEL 21

START: MOV LIM,SP ;SET UP STACK
CLR @#PS ;SET PRIORITY
RESETIOX
0
.BYTE RESEC.0
INIT
HSPCODE
.BYTE INIC.HSP
MOV #4.0#MDXCTL ;DEVICE 2
MOV #3.0#DMXOUT ;RESET OFF AT XBAR
JSR PC.C.X ;TURN OFF FLAGS
MOV CHNL.CHAN ;SET UP CHANNEL
MOV RNG.RANGE ;SET UP RANGE
MOV FUN.FUNC ;SET UP FUNCTION
JSR PC.DACEVL
MOV DAC01.DAC03 ;TRANSFER ENCODED INFO
MOV DAC02.DAC04
JSR PC.DACSUP ;SET UP DATA ACQ.
JSR PC.SENCDE
JSR RS.CTLNOX
DEV0
BIS #100.0#CKSR ;TURN ON CLOCK
WATLP: BIS #PRI07.@#PS
TST CPFLAG
BEQ WA.01
CLR CPFLAG
BIC #PRI07.@#PS
KEYIN
BR WATLP
WA.01: TST DTHFLG ;IS DEPOSITION THROUGH?
BEQ WA.02

```

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37	000204	042737	000340	177776		BIC	#PRI07,@#PS
38	000212	104400				IOWAIT	
39	000214	000001				TTY	
40	000216	000004				WRITE	
41	000220	000242				DTBUF	
42	000222	012	001			.BYTE	WRIC,TTY
43	000224	005067	000000G			CLR	DTHFLG
44	000230	042737	000340	177776	WA.02:	BIC	#PRI07,@#PS
45	000235	000001				WAIT	
46	000240	000741				BR	WATLP
47							
48	000242	000030				DTBUF:	DTBE-DTBS
49	000244	000000					0
50	000246	000030					DTBE-DTBS
51	000250	015	012			DTBS:	.BYTE CR,LF
52	000252	104	105	120			.ASCII /DEPOSITION COMPLETED/
	000255	117	123	111			
	000260	124	111	117			
	000263	116	040	103			
	000266	117	115	120			
	000271	114	105	124			
	000274	107	104				
53	000276	015	012			.BYTE	CR,LF
54	000280					DTBE:	.EVEN
55	000300	000006				HSPCDE:	.WORD 6
56							
57		000001				.END	

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KEYIN

Interprets Commands from Teletype

Prints Response to Teletype on Command

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: KEYIN

:

: REV: 8/4/73

:

.TITLE KEYIN

.GLOBL S.DA,TEMP,D.AMIN

.GLOBL S.KEY,C.X

.GLOBL NPF,TSEC,SEC,MIN,HR

.GLOBL R.FIN,R.STRT,R.TIME,R.DA,R.SEC,RISFLG

.GLOBL S.SEC,S.TIME,S.DA,SOKFLG

.GLOBL D.TIME,D.SEC,D.M,D.D,CREF,D.FLIM

.GLOBL D.DLO,D.DFLO,D.DHI,D.DFHI,DEPFLG,DTHFLG

.GLOBL ALPHA,BETA,A1,A2,B1,B2,C1,C2,C3

.GLOBL M1,M2,M3,CBAR1,CBAR2,CBAR3

.GLOBL MBAR1,MBAR2,MBAR3,E1,E2,E3

.GLOBL P2M10,P2CC0,P2CM0,P1M10,P1M11,P1CC0

.GLOBL P1CC1,P1CM0,P1CM1,P2CM1,P0CC1,P0CC2

.GLOBL P0CM1,P0CM2,FLAST,PCHFLG,AUXFLG

.GLOBL DATIP,RATE

.GLOBL O.ENTR,CTLMDX

000000

000001

000002

000003

104400

000015

000012

177522

000000

KED = 0

TTY = 1

HSR = 2

HSP = 3

IOWAIT = TRAP

CR = 015

LF = 012

DACTL = 177522

DFV3 = 0

37
 38
 39 000000
 40 000001
 41 000002
 42 000003
 43 000004
 44 000005
 45 000006
 46 000007
 47
 48 177776
 49
 50
 51
 52 104001
 53 104002
 54 104004
 55 104007
 56 104011
 57 104013
 58 104015
 59 104017
 60 104022
 61 104023
 62
 63 000200
 64 000100
 65
 66
 67
 68 000011
 69 000012
 70 000013
 71 000014
 72

: REGISTER ASSIGNMENTS

R0	=	%0
R1	=	%1
R2	=	%2
R3	=	%3
R4	=	%4
R5	=	%5
SP	=	%6
PC	=	%7
PS	=	177776

: FPP-11 EMT CALLS

ADDF	=	EMT+1
SUBF	=	EMT+2
MULF	=	EMT+4
MOVF	=	EMT+7
FIX	=	EMT+11
FLT	=	EMT+13
ITOA	=	EMT+15
FTOA	=	EMT+17
ATOI	=	EMT+22
ATOF	=	EMT+23
FAM	=	200
PM	=	100

: IOX COMMAND CODES

REAC	=	11
WRIC	=	12
REARC	=	13
WRIRC	=	14

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73		: IOX CALLS	
74			
75	000004	READ	= 10T
76	000004	WRITE	= 10T
77	000004	READR	= 10T
78	000004	WRITR	= 10T


```

1          000000*          .CSECT
2
3          : GET-NON-BLANK ROUTINE:
4          : R1=BUFFER ↑, R2=END OF BUFFER ↑
5          : ON RETURN V BIT CLEAR = R1 ↑ NEXT NON-BLANK/TAB
6          :          V BIT SET = R1 ↑ END OF BUFFER
7
8 000000 020102          GNB:   CMP      R1,R2          :END OF BUFFER?
9 000002 103012          BHS      GNB.99          :YES
10 000004 121127 000040      CMPB     (R1),#040      :BLANK?
11 000010 001002          BNE      GNB.01          :NO
12 000012 005201          GNB.02: INC      R1          :TRY NEXT BYTE
13 000014 000771          BR       GNB
14 000016 121127 000011      GNB.01: CMPB     (R1),#011      :TAB?
15 000022 001773          BEQ      GNB.02          :YES
16 000024 030242          CLV              :NO--NON BLANK
17 000026 000207          RTS      PC
18 000030 000262          GNB.99: SEV              :END OF BUFFER
19 000032 000207          RTS      PC
20
21          : SEARCH ROUTINE:
22          : R1=BUFFER ↑, R2=END OF BUFFER ↑
23          : R0=SEARCH PROTOTYPE LIST ↑
24          : R3=LIST ITEM # * 2 IF MATCH FOUND, ELSE (R3)=-2
25          : R4=INTERNAL LIST BYTE COUNTER
26          : ON RETURN R1 POINTS TO BYTE AFTER ITEM FOUND OR TO
27          : BYTE AFTER BUFFER END. R3 SET AS ABOVE.
28
29 000034 010146          SRCH:   MOV      R1,-(SP)      :SAVE ↑
30 000036 005003          CLR      R3          :RESET ITEM COUNTER
31 000040 112004          SR.00: MOVR     (R0)+,R4      :GET ITEM LENGTH
32 000042 001416          BEQ      SR.99          :0=END OF LIST
33 000044 011601          MOV      (SP),R1          :START OF STRING
34 000046 004767 177726      SR.01: JSR      PC,GNB      :NEXT NON BLANK
35 000052 102412          BVS      SR.99          :NONE LEFT
36 000054 005304          DEC      R4          :COUNT THE BYTE

```

37	000056	122120		CMPB	(R1)+, (R0)+	:BUFFER:LIST
38	000060	001004		BNE	SR.02	:NO MATCH
39	000062	005704		TST	R4	:LIST ITEM END?
40	000064	003370		BGT	SR.01	:NO
41	000066	005726	SR.TN:	TST	(SP)+	:POP OLD
42	000070	000207		RTS	PC	
43	000072	005723	SR.02:	TST	(R3)+	:ADD 2 TO ITEM CTR
44	000074	060400		ADD	R4,R0	:GO TO NEXT ITEM
45	000076	000760		BR	SR.00	
46	000100	012703	177776	SR.99:	#-2,R3	:END OF LIST
47	000104	000770		BR	SR.TN	

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```

1 000106
2 000106 004767 000002
3 000112 000002
4 000114 104400
5 000116 000001
6 000120 000004
7 000122 002210*
8 000124 014 001
9 000126 000132*
10 000130 000207
11 000132 104400
12 000134 000000
13 000136 000004
14 000140 002234*
15 000142 013 000
16 000144 000150*
17 000146 000207
18 000150 012701 002242*
19 000154 010102
20 000156 006702 002056
21 000162 012700 000212*
22 000166 004767 177642
23 000172 000173 000262*
24 000176 104400
25 000200 000001
26 000202 000004
27 000204 002222*
28 000206 012 001
29 000210 000207
30
31 000212 001
32 000213 130
33 000214 001
34 000215 015
35 000216 002
36 000217 107 117

```

```

S.KEY: JSR PC.KEY.00 ;KEYIN
RTI
KEY.00: IOWAIT
TTY
WRITR ;PROMPT WITH ":"
PROMPT
.BYTE WRIRC.TTY
KEY.01
RTS PC
KEY.01: IOWAIT
KBD
READR ;GET THE REPLY
KBUFF
.BYTE REARC.KBD
KEY.02
RTS PC
KEY.02: MOV #KBIN.R1 ;+ BEGINNING OF BUFFER
MOV R1.R2
ADD KBCT.R2 ;+ END OF BUFFER +1
MOV #CCLIST.R0 ;CONTROL COMMAND LIST
JSR PC.SRCH ;FIND OUT WHAT HE WANTS
JMP @CCROUT(R3) ;JUMP TO PROPER HANDLER
KEY.0: IOWAIT
TTY
WRITE ;TELL HIM: WHAT'S WRONG?
QUERY
.BYTE WRIC.TTY
C.NULL: RTS PC
CCLIST: .BYTE 1 ;STRING LENGTH
.ASCII /X/ ;STRING
.BYTE 1
.BYTE CR
.BYTE 2
.ASCII /GO/

```


37	000221	003			.BYTE	3	
38	000222	114	105	124	.ASCII	/LET/	
39	000225	005			.BYTE	5	
40	000226	120	122	111	.ASCII	/PRINT/	
	000231	116	124				
41	000233	005			.BYTE	5	
42	000234	120	125	116	.ASCII	/PUNCH/	
	000237	103	110				
43	000241	007			.BYTE	7	
44	000242	104	105	120	.ASCII	/DEPOSIT/	
	000245	117	123	111			
	000250	124					
45	000251	005			.BYTE	5	
46	000252	104	105	102	.ASCII	/DEBUG/	
	000255	125	107				
47	000257	000			.BYTE	0	:END OF LIST
48					.EVEN		
49							
50	000260	000176*			KEY.Q		:ERROR ROUTINE
51	000262	000510*			C.X		
52	000264	000213*			C.NULL		
53	000266	000302*			C.GO		
54	000270	000550*			C.LET		
55	000272	001550*			C.PRNT		
56	000274	002044*			C.PNCH		
57	000276	002145*			C.DEPS		
58	000300	000000G			Q.ENTR		

CCROUT:

1	000302				C.G0:		:GO: START DEPOSITION
2	000302	052737	000340	177776	BIS	#340,@#PS	
3	000310	012701	000370*		MOV	#SIS,R1	:START OF SWI LIST TO 0
4	000314	020127	000412*		CG.01:	CMP R1,#SIE2	:END OF LIST?
5	000320	103002			BHIS	CG.02	:YES
6	000322	005031			CLR	@(R1)+	:NO. CLEAR THE SWI
7	000324	000773			BR	CG.01	
8	000326	012701	000412*		CG.02:	MOV #FPS,R1	:START OF FPN LIST TO 0
9	000332	012702	000362*		MOV	#F.0,R2	:↑ FPN OF 0
10	000336	020127	000510*		CG.03:	CMP R1,#FPE	:END OF LIST?
11	000342	103003			BHIS	CG.04	:YES
12	000344	104007			MOVF		
13	000346	011231			MOV	(R2),@(R1)+	:NO. CLEAR THE FPN
14	000350	000772			BF	CG.03	
15	000352	012767	177777	000000G	CG.04:	MOV #-1,RISFLG	:TURN ON RISE
16	000360	000227			RTS	PC	
17							
18	000362	000000	000000	000000	F.0:	.WORD 0,0,0	
19							
20	000370				SIS:		:START OF SWI ↑ FOR 0'ING
21	000370	000000G			RISFLG		
22	000372	000000G			SOKFLG		
23	000374	000000G			DEPFLG		
24	000376	000000G			DTHFLG		
25	000400				SIE1:		:END OF PART 1 - "X"
26	000400	000000G			R.DA		
27	000402	000000G			R.SEC		
28	000404	000000G			S.SEC		
29	000406	000000G			D.SEC		
30	000410	000000G			TSEC		
31	000412				SIE2:		:END OF PART 2 - "GO"
32	000412				FPS:		:START OF FPN ↑ FOR 0'ING
33	000412	000000G			FLAST		
34	000414	000000G			D.FLIM		
35	000416	000000G			C1		
36	000420	000000G			C2		

37 000422 000000G
 38 000424 000000G
 39 000426 000000G
 40 000430 000000G
 41 000432 000000G
 42 000434 000000G
 43 000436 000000G
 44 000440 000000G
 45 000442 000000G
 46 000444 000000G
 47 000446 000000G
 48 000450 000000G
 49 000452 000000G
 50 000454 000000G
 51 000456 000000G
 52 000460 000000G
 53 000462 000000G
 54 000464 000000G
 55 000466 000000G
 56 000470 000000G
 57 000472 000000G
 58 000474 000000G
 59 000476 000000G
 60 000500 000000G
 61 000502 000000G
 62 000504 000000G
 63 000506 000000G
 64 000510

C3
 M1
 M2
 M3
 E1
 E2
 E3
 CBAR1
 CBAR2
 CBAR3
 MBAR1
 MBAR2
 MBAR3
 P2CM0
 P2CC0
 P2CM1
 P1CM0
 P1CM1
 P1CC0
 P1CC1
 P1CM0
 P1CM1
 P2CM1
 P2CC1
 P2CC2
 P3CM1
 P2CM2

FPE:

:END OF FPN ↑

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1	000510			C.X:			:X: STOP EXECUTION
2	000510	952737	000340	177776	BIS	#340,@#PS	:LOCK ALL OUT!!
3	000516	012701	000370		MOV	#SIS,R1	:START OF SWI LIST TO 0
4	000522	020127	000400		CX.01:	R1,#SIE1	:END OF LIST?
5	000526	103002			BHIS	CX.02	:YES
6	000530	005031			CLR	@(R1)+	:NO, CLEAR THE SWI
7	000532	000773			BR	CX.01	
8	000534	004567	0000006		CX.02:	RS,CTLNDX	
9	000540	000000			DEV0		:D/A CONV.
10	000542	005037	177522		CLR	@#DACTL	
11	000546	000207			RTS	PC	

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1	000550				C.LET:			:LET: SET UP A VARIABLE
2	000550	012700	001056*			MOV	#VARLIS,R0	:PROTOTYPES
3	000554	004767	177254			JSR	PC,SRCH	:FIND A MATCH
4	000550	005703				TST	R3	:MATCH?
5	000552	002002				BGE	CL.01	
6	000554	000167	177406		CL.00:	JMP	KEY,0	:SHOW ERROR
7	000570	004767	177204		CL.01:	JSR	PC,GNB	:SKIP BLANKS
8	000574	102773				BVS	CL.00	:BR IF NONE
9	000576	122127	000075			CMPS	(R1)+, #* =	:LOOK FOR "="
10	000502	001372				BNE	CL.01	:NOT FOUND
11	000504	104023				ATOF		:CONVERT TO FPN
12	000506	011167	000214			MOV	(R1),FTEMP	:FTEMP IS PLACE
13	000512	102764				BVS	CL.00	:ERROR
14	000514	000173	001342*			JMP	@VROUT(R3)	:GO TO HANDLER
15								
16	000620	052737	000340	177776	CL.F:	BIS	#340,@#PS	:LOCK OTHERS OUT
17	000626	104007				MOV		:MOVE # TO DST
18	000630	016773	000172	001276*		MOV	FTEMP,@VADR(R3)	
19	000636	000207				RTS	PC	
20	000640	016773	000162	001276*	CL.I:	MOV	FTEMP,@VADR(R3)	:MOVE SWI
21	000646	000207				RTS	PC	
22								
23	000650				CL.DA:			:SET UP A D/A DATUM
24	000650	104004				MULF		:SCALE 0-999 TO 0-4095
25	000652	016767	000156	000146		MOV	F.C0,FTEMP	:FTEMP*4095/999
26	000650	102002				BVC	+.6	
27	000652	005726			CL.DA1:	TST	(SP)+	:POP RTN ADR
28	000654	000737				BR	CL.00	:ERROR
29	000656	104011				FIX		:CONVERT TO INTEGER
30	000670	016767	000132	000130		MOV	FTEMP,FTEMP	
31	000676	102771				BVS	CL.DA1	:ERROR
32	000700	026727	000122	007777		CMF	FTEMP,#4095.	: & <= 4095
33	000706	003365				BGT	CL.DA1	
34	000710	000207				RTS	PC	
35								
36	000712				CL.PWR:			:LET A POWER SETTING

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OF POOR QUALITY

37	000712	004767	177732		JSR	PC,CL.DA		
38	000716	000750			BR	CL.I	:STORE IT	
39								
40	000720				CL.DST:		:LET DEPOSITION POWER	
41	000720	004767	177724		JSR	PC,CL.DA		
42	000724	052737	000340	177776	BIS	#340.0#PS	:LOCK OUT ALL	
43	000732	004767	177702		JSR	PC,CL.I	:STASH SWI	
44	000736	004767	001062		JSR	PC,PATCH4		
45	000742	026327	001276	000000G	CMF	VADR(R3),#D.DLO	:LOW LIMIT?	
46	000750	001005			BNE	CL.DS1	:NO	
47	000752	104007			MOVF		:YES	
48	000754	016767	000046	000000G	MOV	FTEMP,D.DFLO		
49	000762	000207			RTS	PC		
50	000764	104007			CL.DS1:	MOVF	:SAVE HIGH LIMIT FPN	
51	000766	016767	000034	000000G	MOV	FTEMP,D.DFHI		
52	000774	000207			RTS	PC		
53								
54	000776				CL.TIM:		:LET A TIME VALUE	
55	000776	104011			FIX		:DIRECTLY TO INT	
56	001000	016767	000022	000020	MOV	FTEMP,FTEMP		
57	001006	102666			BVS	CL.00	:OVERFLOW	
58	001010	100665			BMI	CL.00	:NOT >=0	
59	001012	000712			BR	CL.I	:SAVE IT	
60								
61	001014				CL.THK:		:LET THICKNESS	
62	001014	104001			ADIF		:GET LAST FREQUENCY	
63	001016	016767	000000G	000002	MOV	FLAST,FTEMP		
64	001024	000675			BR	CL.F	:STORE DIFFERENCE	
65								
66	001026	001034			FTEMP:	.=.+6		
67	001034	164357	040625	100003	F.C0:	.WORD	164357,040625,100003	:4095/999
68	001042	147175	076347	077776	F.C1:	.WORD	147175,076347,077776	:999/4095
69	001050	000000	040000	100000	F.C2:	.WORD	0,040000,100000	:.5

				VARLIS:	:VARIABLE LIST
1	001056			.BYTE	9.
2	001056	011		.ASCII	/FINALRISE/
3	001057	106	111		
	001062	101	114		
	001065	111	123		
4	001070	013		.BYTE	11.
5	001071	111	116	.ASCII	/INITIALRISE/
	001074	124	111		
	001077	114	122		
	001102	123	105		
6	001104	019		.BYTE	8.
7	001105	122	111	.ASCII	/PISETIME/
	001110	105	124		
	001113	115	105		
8	001115	010		.BYTE	8.
9	001116	123	117	.ASCII	/SOAKTIME/
	001121	113	124		
	001124	115	105		
10	001126	011		.BYTE	9.
11	001127	123	117	.ASCII	/SOAKPOWER/
	001132	113	120		
	001135	127	105		
12	001140	013		.BYTE	11.
13	001141	104	105	.ASCII	/DEPOSITTIME/
	001144	117	123		
	001147	124	124		
	001152	115	105		
14	001154	011		.BYTE	9.
15	001155	106	122	.ASCII	/FREDSCALE/
	001160	121	123		
	001163	101	114		
16	001166	012		.BYTE	10.
17	001167	106	122	.ASCII	/FRECOFFSET/
	001172	121	117		
	001175	106	123		
	001200	124			

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18	001201	007			.BYTE	7	
19	001202	122	101	124	.ASCII	/RATESET/	
	001205	105	123	105			
	001210	124					
20	001211	011			.BYTE	9.	
21	001212	124	110	111	.ASCII	/THICKNESS/	
	001215	103	113	116			
	001220	105	123	123			
22	001223	010			.BYTE	8.	
23	001224	115	111	116	.ASCII	/MINPOWER/	
	001227	120	117	127			
	001232	105	122				
24	001234	010			.BYTE	8.	
25	001235	115	101	130	.ASCII	/MAXPOWER/	
	001240	120	117	127			
	001243	105	122				
26	001245	005			.BYTE	5	
27	001246	101	114	120	.ASCII	/ALPHA/	
	001251	110	101				
28	001253	004			.BYTE	4	
29	001254	102	105	124	.ASCII	/BETA/	
	001257	101					
30	001260	002			.BYTE	2	
31	001261	101	061		.ASCII	/A1/	
32	001263	002			.BYTE	2	
33	001264	101	062		.ASCII	/A2/	
34	001266	002			.BYTE	2	
35	001267	102	051		.ASCII	/B1/	
36	001271	002			.BYTE	2	
37	001272	102	062		.ASCII	/B2/	
38	001274	000			.BYTE	0	
39					.EVEN		
40	001276						
41	001276	000000G			R.FIN	:FINAL RISE	:ADDRESS OF VARIABLES
42	001280	000000G			R.STRT	:INITIAL RISE	
43	001302	000000G			R.TIME	:RISE TIME	

VADR:

:ADDRESS OF VARIABLES

44 001304 000000G
45 001306 000000G
46 001310 000000G
47 001312 000000G
48 001314 000000G
49 001316 000000G
50 001320 000000G
51 001322 000000G
52 001324 000000G
53 001326 000000G
54 001330 000000G
55 001332 000000G
56 001334 000000G
57 001336 000000G
58 001340 000000G

S.TIME :SOAK TIME
S.DA :SOAK POWER
D.TIME :DEPOSIT TIME
D.M :FREQ SCALE
D.O :FREQ OFFSET
CREF :RATE SET
D.FLIM :THICKNESS
D.DLO :MIN POWER
D.DHI :MAX POWER
ALPHA
BETA
A1
A2
B1
B2

59
60 001342
61 001342 000712'
62 001344 000712'
63 001346 000776'
64 001350 000776'
65 001352 000712'
66 001354 000776'
67 001356 000620'
68 001358 000620'
69 001360 000620'
70 001364 001014'
71 001366 000720'
72 001370 000720'
73 001372 000620'
74 001374 000620'
75 001376 000620'
76 001380 000620'
77 001382 000620'
78 001384 000620'

VR0UT:

:LET HANDLERS

CL.PWR :FINAL RISE
CL.PWR :INITIAL RISE
CL.TIM :RISE TIME
CL.TIM :SOAK TIME
CL.PWR :SOAK POWER
CL.TIM :DEPOSIT TIME
CL.F :FREQ SCALE
CL.F :FREQ OFFSET
CL.F :RATE SET
CL.THK :THICKNESS
CL.DST :MIN POWER
CL.DST :MAX POWER
CL.F :ALPHA
CL.F :BETA
CL.F :A1
CL.F :A2
CL.F :B1
CL.F :B2

80						
81	001426	001560'			CP.01	:ERROR JUMP
82	001412				VRT1:	:PRINT HANDLERS #1
83	001410	001754'			CP.PR	:FINAL RISE
84	001412	001754'			CP.PR	:INITIAL RISE
85	001414	001604'			CP.I	:RISE TIME
86	001416	001604'			CP.I	:SOAK TIME
87	001420	001754'			CP.PR	:SOAK POWER
88	001412	001604'			CP.I	:DEPOSIT TIME
89	001434	001646'			CP.F	:FREQ SCALE
90	001426	001646'			CP.F	:FREQ OFFSET
91	001430	001646'			CP.F	:RATE SET
92	001432	001646'			CP.F	:THICKNESS
93	001434	001754'			CP.PR	:MIN POWER
94	001436	001754'			CP.PR	:MAX POWER
95	001440	001646'			CP.F	:ALPHA
96	001442	001646'			CP.F	:BETA
97	001444	001646'			CP.F	:A1
98	001446	001646'			CP.F	:A2
99	001450	001646'			CP.F	:B1
100	001452	001646'			CP.F	:B2
101						
102	001454				V2LIST:	:PRINT, PROTOTYPES #2
103	001454	004			.BYTE	4
104	001455	122	101	124	.ASCII	/RATE/
	001460	105				
105	001461	003			.BYTE	3
106	001462	103	122	120	.ASCII	/CRP/
107	001465	003			.BYTE	3
108	001466	103	123	120	.ASCII	/CSP/
109	001471	003			.BYTE	3
110	001472	103	104	120	.ASCII	/CDP/
111	001475	003			.BYTE	3
112	001475	103	122	124	.ASCII	/CRT/
113	001501	003			.BYTE	3
114	001502	103	123	124	.ASCII	/CST/

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115	001505	003			.BYTE	3
116	001506	103	104	124	.ASCII	/CDT/
117	001511	000			.BYTE	0
118						
119	001512				V2ADR:	
120	001512	000000G			RATE	
121	001514	000000G			R.DA	:CRP
122	001516	000000G			S.DA	:CSP
123	001520	000000G			DATMP	:CDP
124	001522	000000G			R.SEC	:CRT
125	001524	000000G			S.SEC	:CST
126	001526	000000G			D.SEC	:CDT
127						
128	001530	002020'			CP.00	:ERROR
129	001532				VRT2:	:PRINT HANDLERS #2
130	001532	001720'			CP.F2	:RATE
131	001534	001744'			CP.PR2	:CRP
132	001536	001744'			CP.PR2	:CSP
133	001540	001744'			CP.PR2	:CDP
134	001542	001636'			CP.I2	:CRT
135	001544	001636'			CP.I2	:CST
136	001546	001636'			CP.I2	:CDT

:VARIABLE ADDRESSES

:ERROR

:PRINT HANDLERS #2

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1	001550				C.PRINT:		:PRINT: VARIABLE VALUES
2	001550	010105			MOV	R1,R5	:SAVE +
3	001552	012700	001056*		MOV	#VARLIS,R0	:PROTOTYPES, PART 1
4	001556	004767	176252		JSR	PC,SRCH	:FIND A MATCH
5	001562	000173	001410*		JMP	@VRT1(R3)	:GO TO HANDLER
6	001560	010501			CP.01: MOV	R5,R1	:RESTORE +
7	001570	012700	001454*		MOV	#V2LIST,R0	:PROTOTYPES, PART 2
8	001574	004767	176234		JSR	PC,SRCH	:FIND A MATCH
9	001600	000173	001532*		JMP	@VRT2(R3)	:GO TO HANDLER
10							
11	001604	017367	001276*	177214	CP.1: MOV	@VADR(R3),FTEMP	:MOVE THE SWI
12							
13	001612	104015			CP.SWI: ITOA		:CONVERT TO ASCII
14	001614	016767	177206	000546	MOV	FTEMP,IBUFS	
15	001622	104400			IOWAIT		
16	001624	000001			TTY		
17	001626	000004			WRITE		
18	001630	002362*			IBUF		
19	001632	012	001		.BYTE	WRIC,TTY	
20	001634	000207			RTS	PC	
21							
22	001636	017367	001512*	177162	CP.12: MOV	@V2ADR(R3),FTEMP	:GET SWI
23	001644	000762			BR	CP.SWI	:PRINT IT
24							
25	001646	013746	177776		CP.F: MOV	@#PS,-(SP)	:SAVE STATUS
26	001652	052737	000340	177776	BIS	#340,@#PS	:LOCK OUT
27	001650	104007			MOV		:MOVE THE FPN
28	001652	017367	001276*	177136	MOV	@VADR(R3),FTEMP	
29							
30	001670	012637	177776		CP.FPN: MOV	(SP)+,@#PS	:RESTORE STATUS
31	001674	104017			FTOA		
32	001676	016767	177124	000504	MOV	FTEMP,FBUFS	
33	001704	104400			IOWAIT		
34	001706	000001			TTY		
35	001710	000004			WRITE		
36	001712	002402*			FBUF		

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37	001714	012	001		.BYTE	WRIC,TTY	
38	001716	000207			RTS	PC	
39							
40	001720	013746	177776	CP.F2:	MOV	@#PS,-(SP)	:SAVE STATUS
41	001724	052737	000340	177776	BIS	#340,@#PS	
42	001732	104007			MOVF		:MOVE FPN
43	001734	017367	001512	177064	MOV	@V2ADR(R3),FTEMP	
44	001742	000752			BR	CP.FPN	
45							
46	001744			CP.PR2:			:PRINT A DEP.PWR
47	001744	017367	001512	177054	MOV	@V2ADR(R3),FTEMP	:MOVE SWI
48	001752	000403			BR	CP.P01	
49							
50	001754			CP.PR:			:PRINT A DEP.PWR
51	001754	017367	001276	177044	MOV	@VADR(R3),FTEMP	:MOVE SWI
52	001762	004767	000036		CP.P01:	JSR	PC,PATCH4
53	001766	104004			MULF		:*999/4095
54	001770	016767	177046	177030	MOV	F.C1,FTEMP	
55	001776	104001			ADDF		:+.5
56	002000	016767	177044	177020	MOV	F.C2,FTEMP	
57	002006	104011			FIX		:ABS()
58	002010	016767	177012	177010	MOV	FTEMP,FTEMP	
59	002016	102275			BVC	CP.SWI	:GO IF OK
60	002020	000167	176152		CP.00:	JMP	KEY.0
61	002024	016767	176776	000374	PATCH4:	MOV	FTEMP,PTEMP
62	002032	104013			FLT		
63	002034	016767	000366	176764	MOV	PTEMP,FTEMP	
64	002042	000207			RTS	PC	
65							

1	002044				C.PNCH:			:PUNCH CONTROL
2	002044	012700	002124'		MOV	#PCHLST.R0		:GET PROTOTYPES
3	002050	004767	175760		JSR	PC.SRCH		:FIND OUT WHAT TO DO
4	002054	000173	002114'		JMP	@PJADR(R3)		:JUMP TO ROUTINE
5	002060	005067	000000G		C.POFF:	CLR	PCHFLG	:PUNCH OFF
6	002064	000207			RTS	PC		
7	002066	012767	177777	000000G	C.PAUX:	MOV	#-1.AUXFLG	:FLAG ON FOR AUX DATA
8	002074	012767	177777	000000G	C.PON:	MOV	#-1.PCHFLG	:PUNCH ON
9	002102	000207			RTS	PC		
10	002104	005067	000000G		C.NPAX:	CLR	AUXFLG	:FLAG OFF
11	002110	000207			RTS	PC		
12	002112	002074'				C.PON		
13	002114	002060'			PJADR:	C.POFF		
14	002116	002074'				C.PON		
15	002120	002066'				C.PAUX		
16	002122	002104'				C.NPAX		
17								
18	002124				PCHLST:			
19	002124	003			.BYTE	3		
20	002125	117	106	106	.ASCII	/OFF/		
21	002130	002			.BYTE	2		
22	002131	117	116		.ASCII	/ON/		
23	002133	003			.BYTE	3		
24	002134	101	125	130	.ASCII	/AUX/		
25	002137	004			.BYTE	4		
26	002140	116	101	125	.ASCII	/NAUX/		
	002143	130						
27	002144	000			.BYTE	0		
28					.EVEN			

1	002146			C.DEPS:	TST	RISFLG	:DEPOSIT
2	002146	005767	000000G		BEQ	.+6	:RISE PHASE?
3	002152	001402					:NO
4	002154	000167	176016	CD.00:	JMP	KEY.0	:ERROR
5	002160	005767	000000G		TST	SOKFLG	:SOAK PHASE?
6	002164	001773			BEQ	CD.00	:ERROR IF NOT
7	002166	005067	000000G		CLR	SOKFLG	:TURN OFF SOAK
8	002172	012767	177777 000000G		MOV	#-1.DEPFLG	:TURN ON DEPOSIT
9	002200	016767	000000G 000000G		MOV	S.DA.TEMP	
10	002206	000207			RTS	PC	

1	002210	000003		PROMPT: PBE-PBS
2	002212	000000		0
3	002214	000003		PBE-PBS
4	002216	015	012	072 PBS: .BYTE CR,LF,':
5	002221			PBE: .EVEN
6	002222	000003		QUERY: QBE-QBS
7	002224	000000		0
8	002226	000003		QBE-QBS
9	002230	077	015	012 QBS: .BYTE '?',CR,LF
10	002233			QBE: .EVEN
11	002234	000120		KBUF: KBE-KBIN
12	002236	000000		0
13	002240	000000		KBCT: 0
14	002242	002362'		KBIN: .=.+80.
15	002362			KBE: .EVEN
16	002362	000011		IBUF: IBE-IBS
17	002364	000000		0
18	002366	000011		IBE-IBS
19	002370	002377'		IBUFS:IBS: .=.+7
20	002377	015	012	.BYTE CR,LF
21	002401			IBE: .EVEN
22	002402	000015		FBUF: FBE-FBS
23	002404	000000		0
24	002406	000015		FBE-FBS
25	002410	002423'		FBUFS:FBS: .=.+11.
26	002423	015	012	.BYTE CR,LF
27	002425			FBE: .EVEN
28	002426	000000		PTMP: .WORD 0
29				
30		000001'		.END

CKI

Transfer Control to Proper Routine on
Clock Interrupt

1		:	
2		:	PDP-11 CLOCK INTERRUPT HANDLER
3		:	
4		:	REV: 7/29/73
5		:	
6		:	CONTENTS:
7		:	1. CKI
8		:	
9		:	THIS MODULE SERVICES THE 1 HERTZ CLOCK INTERRUPT AND
10		:	INITIATES THE CONTROLLER PROCESSES AT THE TIME OF
11		:	THE INTERRUPT.
12		:	
13		:	.TITLE CKI
14		:	.GLOBL CKI.TSEC.SEC.MIN.HR
15		:	
16		:	.GLOBL CTLMDX
17		:	.GLOBL RISFLG
18		:	.GLOBL SOKFLG
19		:	.GLOBL DEPFLG
20		:	
21		:	REGISTER ASSIGNMENTS
22		:	
23	000000	R0	= %0
24	000001	R1	= %1
25	000002	R2	= %2
26	000003	R3	= %3
27	000004	R4	= %4
28	000005	R5	= %5
29	000006	SP	= %6
30	000007	PC	= %7
31			
32	177776	PS	= 177776
33			
34	000000	PRI00	= 0
35	000040	PRI01	= 40
36	000100	PRI02	= 100

37	000140	PRI03	=	140
38	000200	PRI04	=	200
39	000240	PRI05	=	240
40	000300	PRI06	=	300
41	000340	PRI07	=	340
42				
43	177520	CKS	=	177520
44	000000	DEV0	=	0
45				
46	104402	RISE	=	TRAP+2
47	104403	SOAK	=	TRAP+3
48	104404	DEPOS	=	TRAP+4
49				
50	000000			.ASECT
51				
52	000660		=	660
53	000560 000010	CKVEC:	CK1	
54	000662 000240		PRI05	

1	000000				.CSECT		
2	000000	000000			TSEC:	.WORD	0
3	000002	000000			SEC:	.WORD	0
4	000004	000000			MIN:	.WORD	0
5	000006	000000			HR:	.WORD	0
6							
7	000010	042737	000100	177520	CK1:	BIC	#100.@#CKS
8	000016	005267	177756			INC	TSEC
9	000022	005267	177754			INC	SEC
10	000026	026727	177750	000074		CMP	SEC.#50.
11	000034	002422				BLT	CK.01
12	000036	005067	177740			CLR	SEC
13	000042	005267	177736			INC	MIN
14	000046	026727	177732	000074		CMP	MIN.#50.
15	000054	002412				BLT	CK.01
16	000056	005067	177722			CLR	MIN
17	000062	005267	177720			INC	HR
18	000066	026727	177714	000030		CMP	HR.#24.
19	000074	002402				BLT	CK.01
20	000076	005067	177704			CLR	HR
21	000102				CK.01:		
22	000102	005767	000000G			TST	RISFLG
23	000106	001401				BEQ	CK.02
24	000110	104402				RISE	
25	000112	005767	000000G		CK.02:	TST	SOKFLG
26	000116	001401				BEQ	CK.03
27	000120	104403				SOAK	
28	000122	005767	000000G		CK.03:	TST	DEPFLG
29	000126	001401				BEQ	CK.04
30	000130	104404				DEPOS	
31	000132				CK.04:		
32	000132	012737	000204	000660		MOV	#CK.INT.@#CKVEC
33	000140	004567	000000G			JSR	R5.CTLMDX
34	000144	000000				DEV0	
35	000146	052737	000100	177520		BIS	#100.@#CKS
36	000154	042737	000040	177776		BIC	#PRI01.@#PS

:TURN CLOCK INT OFF
:TOTAL SECONDS
:KEEP TIME

:RISE ACTIVE?
:NO
:YES - TRAP
:SOAK ACTIVE?
:NO
:YES - TRAP
:DEPOSITION ACTIVE?
:NO
:YES - TRAP

:SET UP DUMMY INT
:SET UP CLOCK
:TURN ON CLOCK
:LOWER PRIORITY TO 4

37	000162	000040		NOP		:LET INT THRU
38	000164	000040		NOP		
39	000165	052737	000240 177776	BIS	#PRI05,@#PS	:LOCK OUT IF NO INT
40	000174	012737	000010* 000660	CK.05: MOV	#CKI,@#CKVEC	:RESTORE VECTOR
41	000202	000002		RTI		
42	000204	002626		CK.INT: CMP	(SP)+,(SP)+	:POP INT TRASH
43	000206	000772		BR	CK.05	:CLEAN UP
44						
45		000001*		.END		

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TRPHND

Services Software Trap Instructions

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;
; PDP-11 TRAP HANDLER
;
; REV: 8/1/73
;
; CONTENTS:
;   1. TRPHND
;   2. S.IOW
;
; THIS MODULE SERVICES THE "TRAP" INSTRUCTION
; AND THE "IOWAIT" TRAP CALL.
;
; .TITLE TRPHND
; .GLOBL TRPHND
;
; .ASECT
; = 34 ;TRAP VECTOR
; TRPHND
; 340 ;RPIORITY 7
;
; .CSECT
;
; SP = %6
; PC = %7
; PS = 177776
;
; .GLOBL S.IOW ;IOWAIT
; .GLOBL S.KEY ;KEYIN
; .GLOBL S.RISE ;RISE
; .GLOBL S.SOAK ;SOAK
; .GLOBL S.DEP ;DEPOS
;
; TRPHND: MOV 2(SP),-(SP) ;RESTORE USER PRIORITY
; BIC #177437,(SP) ;CLEAR T BIT, ETC.
; BIS (SP)+,0#PS
; MOV (SP),-(SP) ;ADDR+2 OF TRAP INSTR

```

37	000016	162716	000002	SUB	#2,(SP)	:↑ TRAP INSTR
38	000022	013646		MOV	@(SP)+,(SP)	:REPLACE W/TRAP INSTR
39	000024	042716	177400	BIC	#177400,(SP)	:LEAVE ONLY TRAP #
40	000030	006316		ASL	(SP)	:*2 FOR BYTES TO WORDS
41	000032	062716	000042*	ADD	#TRPTBL,(SP)	:NOW POINTS TO ROUTINE
42	000036	013646		MOV	@(SP)+,(SP)	: ADDR.: NOW TO ITSELF
43	000040	012607		MOV	(SP)+,PC	:GO...RETURN WITH RTI
44						
45	000042	000054*		TRPTBL: S.IOW	:IOWAIT 000	
46	000044	000000G		S.KEY	:KEYIN 001	
47	000046	000000G		S.RISE	:RISE 002	
48	000050	000000G		S.SOAK	:SOAK 003	
49	000052	000000G		S.DEP	:DEPOS 004	

ORIGINAL PAGE IS
POOR QUALITY


```

1      ;
2      ; IOWAIT SERVICE ROUTINE
3      ;
4
5      000340      PRI07      =      340
6      000004      WAITR      =      10T
7      000004      WAITC      =      4
8
9 000054 117667 000000 000017 S.IOW: MOVB @(SP),IOW.00 :GET THE SLOT #
10 000052 062716 000002      ADD      #2.(SP) :MOVE USER PC PAST IT
11 000066 052737 000340 177776 IOW.01: BIS      #PRI07.0#PS :LOCK OUT OTHERS
12 000074 000004      WAITR      :CHECK WITH IOW
13 000076 000104      IOW.02
14 000100      .BYTE      WAITC
15 000101      000      IOW.00: .BYTE      0 :SLOT # GOES HERE
16 000102 000002      RTI      :UNBUSY..RETURN
17 000104 042737 000340 177776 IOW.02: BIC      #PRI07.0#PS :LOWER PRIORITY
18 000112 000001      WAIT      :WAIT FOR INTERRUPT
19 000114 000764      BR      IOW.01 :THEN ASK AGAIN
20
21      000001      .END

```

ORIGINAL PAGE IS
OF POOR QUALITY

RISE

Calculates Rise Increment

Steps D/A Each Second

Passes Control to Soak Routine

```

1      ;
2      ; RISE ROUTINE
3      ;
4      ; REV:      4/13/74
5      ;
6      ; CONTENTS:
7      ;      1. S.RISE
8      ;
9      ; THIS MODULE CONTROLS THE D/A CONVERTER OUTPUT
10     ; DURING THE RISE PHASE OF DEPOSITION CONTROL.
11     ;
12     ; VARIABLES:
13     ;
14     ; R.FIN (SWI) FINAL SETPOINT, D/A CONVERTER
15     ; R.STRT(SWI) INITIAL SETPOINT, D/A CONVERTER
16     ; R.TIME(SWI) NUMBER OF SECONDS OF RISE TIME
17     ; R.DA  (SWI) CURRENT D/A CONVERTER SETTING
18     ; R.SEC (SWI) CUMULATIVE RISE TIME, SECONDS
19     ; RISFLG(SWI) FLAG: 0=RISE PHASE OFF, -1=RISE PHASE ON
20     ;
21     .TITLE  RISE
22     .GLOBL  MCOUNT,STORAT
23     .GLOBL  C1,XVEC      ;FOR CLEARING VARIABLES
24     .GLOBL  NCOUNT
25     .GLOBL  S.RISE,R.FIN,R.STRT,R.TIME,R.DA,RISFLG
26     .GLOBL  R.SEC
27
28     .GLOBL  CTLMDX,SOKFLG
29
30     000000      DEV0      =      0
31     177522      DACTL     =      177522
32     000001      TTY       =      1
33     000015      CR        =      015
34     000012      LF        =      012
35     104400      IOWAIT    =      TRAP
36

```


37		: REGISTER ASSIGNMENTS
38		
39	000000	R0 = %0
40	000001	R1 = %1
41	000002	R2 = %2
42	000003	R3 = %3
43	000004	R4 = %4
44	000005	R5 = %5
45	000006	SP = %6
46	000007	PC = %7
47		
48		: FPP-11 EMT CALLS
49		
50	104015	ITOA = EMT+15
51	104033	MUL = EMT+33
52	104034	DIV = EMT+34
53		
54		: IOX COMMAND CODES
55		
56	000012	WRIC = 12
57		
58		: IOX CALLS
59		
60	000004	WRITE = IOT

1	000000			.CSECT		
2						
3	000000	000000		R.FIN:	.WORD	0
4	000002	000000		R.STRT:	.WORD	0
5	000004	000000		R.TIME:	.WORD	0
6	000006	000000		R.DA:	.WORD	0
7	000010	000000		R.SEC:	.WORD	0
8	000012	000000	000000	R.INC:	.WORD	0,0
9	000016	000000		RISFLG:	.WORD	0
10						
11	000020	016767	177754 177764	S.RISE:	MOV	R.FIN,R.INC ;COMPUTE THE RISE INCR.
12	000026	010146			MOV	R1,-(SP)
13	000030	010046			MOV	R0,-(SP)
14	000032	012700	000000G		MOV	#C1,R0
15	000036	012701	000000G		MOV	#XVEC,R1
16	000042	005020		CLEAR:	CLR	(R0)+
17	000044	020001			CMP	R0,R1
18	000046	001375			BNE	CLEAR
19	000050	012700	000000G		MOV	#STORAT,R0
20	000054	010001			MOV	R0,R1
21	000056	062701	000132		ADD	#90.,R1
22	000062	005020		CLEAR2:	CLR	(R0)+
23	000064	020001			CMP	R0,R1
24	000066	001375			BNE	CLEAR2
25	000070	005067	000000G		CLR	NCOUNT
26	000074	005067	000000G		CLR	MCOUNT
27	000100	012600			MOV	(SP)+,R0
28	000102	012601			MOV	(SP)+,R1
29	000104	166767	177672 177700		SUB	R.STRT,R.INC
30	000112	003463			ELE	R1,99
31	000114	005067	177674		CLR	R.INC+2 ;ERROR IF R.FIN=R.STRT
32	000120	104034			DIV	;DWI REQ'D FOR DIV
33	000122	016767	177656 177662		MOV	R.TIME,R.INC ;(R.FIN-R.STRT)/R.TIME
34	000130	102454			BVS	R1,99 ;IF DIVISOR TOO SMALL
35	000132	005767	177654		TST	R.INC ;SEE IF OK
36	000136	003003			BGT	R1,01 ;>0, OK

37	000140	012767	000001	177644	MOV	#1,R,INC	:IF TOO SMALL, MAKE 1
38	000146	005767	177634		RI.01: TST	R,DA	:IS THIS START OF RISE?
39	000152	001004			BNE	RI,04	:NO
40	000154	016767	177622	177624	MOV	R,STRT,R,DA	:YES, SET D/A UP
41	000162	000412			BR	RI,02	
42	000164	066767	177622	177614	RI.04: ADD	R,INC,R,DA	:STEP D/A ONWARD
43	000172	026767	177610	177600	CMP	R,DA,R,FIN	:ARE WE AT END?
44	000200	101403			BLOS	RI,02	:NO
45	000202	016767	177572	177576	MOV	R,FIN,R,DA	:YES, SET TO FINAL
46	000210	005267	177574		RI.02: INC	R,SEC	:COUNT TIME
47	000214	026767	177570	177562	CMP	P,SEC,R,TIME	:OUT OF TIME?
48	000222	101410			BLOS	RI,03	:NO
49	000224	005067	177560		CLR	R,SEC	:YES
50	000230	005067	177562		CLR	RISFLG	
51	000234	011767	177777	000000G	MOV	#-1,SOKFLG	
52	000242	000002			RTI		
53	000244	004567	000000G		RI.03: JSR	R5,CTLMDX	
54	000250	000000			DEV0		:SET UP D/A
55	000252	016737	177530	177522	MOV	R,DA,@#DACTL	:REFRESH SETTING
56	000260	000002			RTI		
57	000262	005067	177520		RI.99: CLR	R,DA	:ON ERROR, RESET ALL
58	000266	005067	177516		CLR	R,SEC	
59	000272	005067	177520		CLR	RISFLG	
60	000276	004567	000000G		JSR	R5,CTLMDX	
61	000302	000000			DEV0		
62	000304	005037	177522		CLR	@#DACTL ;TURN D/A OFF	
63	000310	104015			ITOA		:PRINT OUT THE ERROR
64	000312	016767	177462	000132	MOV	R,FIN,R,FOUT	
65	000320	104015			ITOA		
66	000322	016767	177454	000100	MOV	R,STRT,R,SOOT	
67	000330	104015			ITOA		
68	000332	016767	177446	000133	MOV	R,TIME,R,TOOT	
69	000340	104100			IOWAIT		:WAIT ON TTY
70	000342	000001			TTY		
71	000344	000004			WRITE		:START I/O
72	000346	000354			R,CBUF		

73	000350	012	001		.BYTE	WRIC,TTY
74	000352	000002			RTI	
75						
76	000354	000122			R.EBUF:	RBE-RBS
77	000356	000000				0
78	000360	000122				RBE-RBS
79	000362	015	012		RBS:	.BYTE CR,LF
80	000364	111	116	126		.ASCII /INVALID RISE PARAMETERS:/
	000367	101	114	111		
	000372	104	040	122		
	000375	111	123	105		
	000400	040	120	101		
	000403	122	101	115		
	000406	105	124	105		
	000411	122	123	072		
81	000414	015	012		.BYTE	CR,LF
82	000416	123	124	101	.ASCII	@START D/A:@
	000421	122	124	040		
	000424	104	057	101		
	000427	072				
83	000430	000437			RSOUT:	.=.+7
84	000437	105	111	116		.ASCII @FINISH D/A:@
	000442	111	123	110		
	000445	040	104	057		
	000450	101	072			
85	000452	000461			RFOUT:	.=.+7
86	000461	122	111	123		.ASCII /RISE TIME:/
	000464	105	040	124		
	000467	111	115	105		
	000472	072				
87	000473	000502			RTOUT:	.=.+7
88	000502	015	012			.BYTE CR,LF
89	000504				RBE:	.EVEN
90	000504	000000			STORER:	.WORD 0
91	000001					.END

ORIGINAL PAGE IS
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SOAK

Maintains D/A at Final Rise Value

Counts Seconds of Execution

Passes Control to Deposition Routine

1				
2			:	
3			:	SOAK ROUTINE
4			:	
5			:	REV: 8/3/73
6			:	
7			:	CONTENTS:
8			:	1. S.SOAK
9			:	
10			:	THIS MODULE CONTROLS THE D/A CONVERTER OUTPUT
11			:	DURING THE SOAK PHASE OF DEPOSITION CONTROL.
12			:	
13			:	VARIABLES:
14			:	
15			:	S.SEC (SWI) ELAPSED SOAK TIME, SECONDS
16			:	S.TIME(SWI) SOAK TIME SETPOINT, SECONDS
17			:	S.DA (SWI) SOAK PHASE D/A CONVERTER SETTING
18			:	SOKFLG(SWI) FLAG: 0=SOAK OFF, -1=SOAK ON
19			:	
20				.TITLE SOAK
21				.GLOBL TEMP,D.AMIN
22				.GLOBL S.SOAK,S.SEC,S.TIME,SOKFLG,S.DA
23				
24				.GLOBL CTLNDX,DEPFLG,R.DA
25	000000	DEV0	=	0
26	177522	DACTL	=	177522
27				
28			:	REGISTER ASSIGNMENTS
29				
30	000000	R0	=	%0
31	000001	R1	=	%1
32	000002	R2	=	%2
33	000003	R3	=	%3
34	000004	R4	=	%4
35	000005	R5	=	%5
36	000006	SP	=	%6

37	000007	PC	=	%7
38				
39	177776	PS	=	177776
40				

1	000000'			.CSECT		
2						
3	000000	000000		S.SEC:	.WORD	0
4	000002	000004'		S.TIME:	.=.+2	
5	000004	000000		S.DA:	.WORD	0
6	000006	000000		SOKFLG:	.WORD	0
7						
8	000010	005767	177764	S.SOAK:	TST	S.SEC ;FIRST TIME THRU?
9	000014	001003			BNE	S.CNT ;NO
10	000016	016767	000000G 177760		MOV	R.DA,S.DA ;PICK UP D/A SETTING
11	000024	005267	177750	S.CNT:	INC	S.SEC ;COUNT TIME
12	000030	026767	177744 177744		CMP	S.SEC,S.TIME ;ARE WE THROUGH?
13	000036	003007			BGT	S.FIN ;YES
14	000040	004567	000000G		JSP	R5,CTLMDX ;NO
15	000044	000000			DEVB	
16	000046	016737	177732 177522		MOV	S.DA,@#DACTL ;SET D/A
17	000054	000002			RTI	
18	000056	005037	177724	S.FIN:	CLR	SOKFLG
19	000062	005067	177712		CLR	S.SEC
20	000066	012767	177777 000000G		MOV	#-1,DEPFLG
21	000074	016767	177704 000030G		MOV	S.DA,TEMP ;STORE THE SOAK VALUE
22	000102	000002			RTI	
23		000001'			.END	

DEPOS

Obtains Freq. Value
Calculates Rate Value
Calls APPASX Routine
Compares D/A Value for Max/Min
Assigns Multiplexer Channels
Sets D/A Values
Commands Punch Routine

```

1      ;
2      ; DEPOSITION ROUTINE
3      ;
4      ; REV: 6/19/74
5      ;
6      ; CONTENTS:
7      ;     1. S.DEP
8      ;     2. DASET
9      ;
10     ; THIS MODULE CONTROLS THE D/A CONVERTER OUTPUT DURING
11     ; THE ACTUAL DEPOSITION PHASE. IT RELIES UPON MODULE
12     ; APASSX TO COMPUTE THE CONTROL VARIABLE. ENTRY DASET
13     ; IS CALLED FROM APASSX TO SET UP THE D/A CONVERTER.
14     ;
15     ; VARIABLES:
16     ;
17     ; D.TIME(SWI) DEPOSITION TIME LIMIT, SECONDS
18     ; D.SEC (SWI) CURRENT ELAPSED DEPOSITION TIME, SECONDS
19     ; D.M (FPN) SCALE MULTIPLIER, USED IN CONVERSION OF
20     ; IDVM READING IN VOLTS TO FREQUENCY
21     ; D.O (FPN) SCALE OFFSET, VOLTAGE TO FREQUENCY
22     ; CREF (FPN) DESIRED RATE, HERTZ/SECOND
23     ; D.FLIM(FPN) LIMIT OF DEPOSITION FREQUENCY
24     ; D.DLO (SWI) LOWER LIMIT, D/A SETTING
25     ; D.DFLO(FPN) LOWER LIMIT, D/A SETTING
26     ; D.DHI (SWI) UPPER LIMIT, D/A SETTING
27     ; D.DFHI(FPN) UPPER LIMIT, D/A SETTING
28     ; DEPFLG(SWI) FLAG: 0=DEPOSITION PHASE OFF, -1=ON
29     ; DTHFLG(SWI) FLAG: 0=DEPOSITION NOT FINISHED, -1=FIN.
30     ; PCHFLG(SWI) FLAG: 0=NO DATA PUNCHED, -1=PUNCH DATA
31     ; AUXFLG(SWI) FLAG: 0=NO PUNCH ALPHA-B2, -1=PUNCH
32     ; DATMP (SWI) DEPOSITION POWER, CURRENT
33     ; RATE (FPN) CURRENT RATE
34     ; FLAST (FPN) CURRENT FREQUENCY
35     ;
36     .TITLE DEPOS

```


37	.GLOBL	STORER
38	.GLOBL	AVERAT
39	.GLOBL	COUNT,NUMBER
40	.GLOBL	MCOUNT,MNUM
41	.GLOBL	ADD,D.DSTG
42	.GLOBL	XVEC
43	.GLOBL	S.DEP,DASET
44	.GLOBL	D.TIME,D.SEC,D.M,D.O,D.FLIM
45	.GLOBL	D.DLO,D.DFLO,D.DH1,D.DFH1
46	.GLOBL	CREF,ALPHA,BETA
47	.GLOBL	A1,A2,B1,B2
48	.GLOBL	C1,C2,C3,M1,M2,M3
49	.GLOBL	E1,E2,E3
50	.GLOBL	ARR1,NEQ,DEPFLG,DTHFLG,DATMP,RATE
51	.GLOBL	PCHFLG,AUXFLG,FLAST
52		
53	.GLOBL	CTLMDX,SIMUL,APASS1,APASS2,APASS3
54	.GLOBL	ENCODE,BCDTON
55	.GLOBL	METER,DVMH1,DVMLO,DVM1,DVM2
56		

: REGISTER ASSIGNMENTS

59	000000	R0	=	%0
60	000001	R1	=	%1
61	000002	R2	=	%2
62	000003	R3	=	%3
63	000004	R4	=	%4
64	000005	R5	=	%5
65	000006	SP	=	%6
66	000007	PC	=	%7
67				
68	177776	PS	=	177776
69				

: FPP-11 EMT CALLS

72	104001	ADDF	=	EMT+1
----	--------	------	---	-------

73	104002	SUBF	=	ENT+2
74	104003	NEGF	=	ENT+3
75	104004	MULF	=	ENT+4
76	104005	DIVF	=	ENT+5
77	104007	MOVF	=	ENT+7
78	104010	CMPF	=	ENT+10
79	104011	FIX	=	ENT+11
80	104013	FLT	=	ENT+13
81	104033	MUL	=	ENT+33
82	104034	DIV	=	ENT+34
83				
84	000200	FAM	=	200
85	000100	PM	=	100
86				
87		; IOX COMMAND CODES		
88				
89	000005	SEEC	=	5
90	000012	WRIC	=	12
91				
92		; IOX CALLS		
93				
94	000004	SEEK	=	10T
95	000004	WRITE	=	10T
96				
97	000001	TTY	=	1
98	000003	HSP	=	3
99	000015	CR	=	015
100	000012	LF	=	012
101	104400	IOWAIT	=	TRAP
102	177522	DACTL	=	177522
103	000000	DEV0	=	0
104				

1	000000'				.CSECT	
2	000000	000000			DEPFLG: .WORD	0
3	000002	000000			DTHFLG: .WORD	0
4	000004	000000			PCHFLG: .WORD	0
5	000006	000000			AUXFLG: .WORD	0
6	000010	000012'			D.TIME: .=.+2	
7	000012	000014'			D.SEC: .=.+2	
8	000014	103453	072232	100013	D.M: .WORD	103453,072232,100013 :1865.658
9	000020	074550	123136	100006	D.O: .WORD	074550,123136,100006 :-44.81548
10	000030	000036'			CREF: .=.+6	
11	000036	000042'			D.DLO: .=.+2	
12	000040	000046'			D.DFLO: .=.+6	
13	000046	000050'			D.DHI: .=.+2	
14	000050	000056'			D.DFHI: .=.+6	
15	000056	000064'			D.FLIM: .=.+6	
16	000064	000072'			ALPHA: .=.+6	:DO 1
17	000072	000100'			BETA: .=.+6	:NOT 2
18	000100	000106'			A1: .=.+6	:DISTURB3
19	000106	000114'			A2: .=.+6	:THE 4
20	000114	000122'			B1: .=.+6	:ORDER 5
21	000122	000130'			B2: .=.+6	:HERE 6
22	000130	000136'			C1: .=.+6	
23	000136	000144'			C2: .=.+6	
24	000144	000152'			C3: .=.+6	
25	000150	000160'			M1: .=.+6	
26	000160	000166'			M2: .=.+6	
27	000166	000174'			M3: .=.+6	
28	000174	000202'			E1: .=.+6	
29	000202	000210'			E2: .=.+6	
30	000210	000216'			E3: .=.+6	
31	000216	000246'			XVEC: .=.+24.	
32	000246	000476'			ARR1: .=.+120.	
33	000476	000480'			NEO: .=.+2	
34	000480	000482'			D.RSTG: .=.+18.	
35	000482	000470'			D.DSTG: .=.+6.	

ORIGINAL PAGE IS
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1	000470		S.DEF:		:DEPOS
2	000470	010546	MOV	R5, -(SP)	
3	000472	010446	MOV	R4, -(SP)	
4	000474	010346	MOV	R3, -(SP)	
5	000476	010246	MOV	R2, -(SP)	
6	000500	010146	MOV	R1, -(SP)	
7	000502	010046	MOV	R0, -(SP)	
8	000504	005767	177302	TST	D.SEC :1ST TIME THRU?
9	000510	001540		BEQ	DFIRST :YES
10	000512	026767	177274 177270	CMP	D.SEC,D.TIME :TIME LIMIT EXCEEDED?
11	000520	003402		BLE	.+6
12	000522	000167	000370	JNP	DTHRU
13	000526	004767	001004	JSR	PC,PMTNTR :NO--MEASURE FREQ.
14	000532	104007		MOVF	:GET THE RATE
15	000534	011067	001206	MOV	(R0),RATE
16	000540	104002		SUBF	
17	000542	011167	001200	MOV	(R1),RATE
18	000546	104007		MOVF	:REPLACE OLD FREQ W/NEW
19	000550	011011		MOV	(R0),(R1)
20	000552	005767	177302	TST	D.FLIM+2 :IS A FREQ LIM. SET?
21	000556	001404		BEQ	DE.01 :NO
22	000560	104010		CMPL	:YES-SEE IF FREQ>=LIMIT
23	000562	011167	177270	MOV	(R1),D.FLIM :FREQ:SETPOINT
24	000566	002153		BGE	DTHRU :FINISHED
25	000570	012700	001742	DE.01: MOV	#D.SS,R0 :+
26	000574	016720	177212	MOV	D.SEC,(R0)+ :TEMP STORE
27	000600	005010		CLR	(R0) :DWI
28	000602	005340		DEC	-(R0) :0-ORIGIN
29	000604	104034		DIV	
30	000606	016710	001176	MOV	D.3,(R0) :D.SEC/3
31	000612	005720		TST	(R0)+ :BACK UP TO 2ND WORD
32	000614	005710		TST	(R0) :1ST PASS?
33	000616	001002		BNE	DE.03 :NO
34	000620	004767	000534	JSR	PC,PCHDTA :YES-DO PUNCHING NOW
35	000624	011001		DE.03: MOV	(R0),R1 :GET REMAINDER 0-2
36	000626	006301		ASL	R1 :BYTES TO WORDS

37	000630	004767	000000G	JSR	PC,AVERAT	
38	000634	104007		MOVF		:MOVE RATE TO PROPER C
39	000636	016771	001104 001774'	MOV	RATE,@CTBL(R1)	
40	000644	104007		MOVF		:MOVE TO SAFE PLACE(TOO
41	000646	016771	001074 001766'	MOV	RATE,@RTBL(R1)	
42	000654	010600		MOV	SP,R0	:FORM R0 STACK
43	000656	162706	000074	SUB	#60,,SP	: FROM SP STACK
44	000662	005267	001066	INC	MCOUNT	
45	000666	026767	001062 001062	CMP	MCOUNT,INUM	
46	000674	001033		BNE	DE.02	
47	000676	005067	001052	CLR	MCOUNT	
48	000702	104003		NEGF		
49	000704	016767	177204 177166	MOV	B1,A1	
50	000712	104010		CMPF		
51	000714	016767	177160 177172	MOV	A1,B1	
52	000722	001001		BNE	CHANG3	
53	000724	000410		BR	PAT1	
54	000726	104003		CHANG3: NEGF		
55	000730	016767	177160 177142	MOV	B1,A1	
56	000736	104007		MOVF		
57	000740	016767	177134 177146	MOV	A1,B1	
58	000746	004771	002002'	PAT1: JSR	PC,@PTBL(R1)	:DO APASSX
59	000752	026727	000766 000002	CMP	D.SS+2,#2	:PASS 3?
60	000760	001001		BNE	DE.02	:NO
61	000762	000400		BR	DE.02	
62	000764	005267	177022	DE.02: INC	D.SEC	:COUNT TIME
63	000770	062706	000074	ADD	#60,,SP	:THROW AWAY STACK AT R0
64	000774	012600		RTN: MOV	(SP)+,R0	
65	000776	012601		MOV	(SP)+,R1	
66	001000	012602		MOV	(SP)+,R2	
67	001002	012603		MOV	(SP)+,R3	
68	001004	012604		MOV	(SP)+,R4	
69	001006	012605		MOV	(SP)+,R5	
70	001010	000002		RTI		
71	001012	004767	000520	DFIRST: JSR	PC,RMTR	:GET INITIAL READING
72	001016	104007		MOVF		

ORIGINAL PAGE IS
OF POOR QUALITY

C-11

73	001020	011011		MOV	(R0),(R1)	:MOVE METER TO FLAST
74	001022	005267	176764	INC	D.SEC	
75	001026	005067	000732	CLR	BLKCT	
76	001032	005767	176746	TST	PCHFLG	:PUNCHING DATA?
77	001036	001756		BEQ	RTN	:NO
78	001040	000004		SEEK		:YES, START IT UP
79	001042	000000		0		
80	001044	005	003	.BYTE	SEEC.HSP	
81	001046	104400		IOWAIT		
82	001050	000003		HSP		
83	001052	000004		WRITE		:PUNCH NULLS
84	001054	001510		NULBUF		
85	001056	012	003	.BYTE	WRIC.HSP	
86	001060	012701	000440	MOV	#D.RSTG.R1	
87	001064	012702	000011	MOV	#9..R2	:3 FPN * 3 WORDS PER
88	001070	005021		D.I01: CLR	(R1)+	:CLEAR OLD RATES
89	001072	005302		DEC	R2	
90	001074	003375		BGT	D.I01	
91	001076	012701	000462	MOV	#D.DSTG.R1	
92	001102	012702	000003	MOV	#3..R2	
93	001106	005021		D.I02: CLR	(R1)+	:CLEAR OLD D/A
94	001110	005302		DEC	R2	
95	001112	003375		BGT	D.I02	
96	001114	000727		BR	RTN	
97	001116	004567	000000G	DTHRU: JSR	R5,CTLM DX	
98	001122	000000		DEV0		
99	001124	005037	177522	CLR	@#DACTL	:TURN OFF D/A
100	001130	005067	176644	CLR	DEPFLG	
101	001134	012767	177777	MOV	#-1.DTHFLG	:FLAG DEPOSITION AS THRU
102	001142	005767	176632	TST	PCHFLG	:PUNCH?
103	001146	001712		BEQ	RTN	:NO
104	001150	012700	001742	MOV	#D.SS.R0	:↑
105	001154	016720	176632	MOV	D.SEC.(R0)+	:SECONDS OF DEPOSITION
106	001160	005010		CLR	(R0)	
107	001162	005340		DEC	-(R0)	
108	001164	104034		DIV		:1/3

ORIGINAL PAGE IS
OF POOR QUALITY

109 001166 016710 000616
 110 001172 005720
 111 001174 004757 000160
 112 001200 104400
 113 001202 000003
 114 001204 005257 000554
 115 001210 012701 001642
 116 001214 016741 176572
 117 001220 016741 000540
 118 001224 012741 000004
 119 001230 000004
 120 001232 001630
 121 001234 012 003
 122 001236 000656
 123
 124 001240 010246
 125 001242 010146
 126 001244 012501
 127 001246 012702 002022
 128 001252 104010
 129 001254 011167 176560
 130 001260 003006
 131 001262 016712 176550
 132 001266 104007
 133 001270 016711 176544
 134 001274 000414
 135 001276 104010
 136 001300 011167 176544
 137 001304 002405
 138 001306 016712 176534
 139 001312 104007
 140 001314 016711 176530
 141 001320 000402
 142 001322 104011
 143 001324 011112
 144 001326 004557 000000

MOV D.3.(R0)
 TST (R0)+
 JSR PC,PCHDTA ;ADJUST ↑ TO REMAINDER
 ;PUNCH REST OF DATA
 IOWAIT
 HSP
 INC BLKCT ;WRITE LAST BLOCK
 ;↑
 MOV #PBUFS+4,R1
 MOV D.SEC.-(R1)
 MOV BLKCT.-(R1)
 MOV #4.-(R1) ;BYTE COUNT
 WRITE
 PBUF
 .BYTE
 BR WRIC,HSP
 RTN
 DASET: MOV R2.-(SP)
 MOV R1.-(SF)
 MOV (R5)+,R1
 MOV #DATMP,R2 ;↑
 CMPF
 MOV (R1).D.DFLO
 BGT DAS.01
 MOV D.DLO.(R2)
 MOVF
 MOV D.DFLO.(R1)
 BR DAS.03
 DAS.01: CMPF
 MOV (R1).D.DFHI
 BLT DAS.02
 MOV D.DHI.(R2)
 MOVF
 MOV D.DFHI.(R1)
 BR DAS.03
 DAS.02: FIX
 MOV (R1).(R2)
 DAS.03: JSR R5.CTLMDX

ORIGINAL PAGE IS
OF POOR QUALITY

145	001332	000000	DEV0		
146	001334	004767	JSR	PC.ADD	
147	001340	016701	MOV	D.SS+2,R1	:GET PASS #
148	001344	005301	ASL	R1	
149	001346	011261	MOV	(R2).D.DSTG(R1)	
150	001352	012601	MOV	(SP)+.R1	
151	001354	012602	MOV	(SP)+.R2	
152	001356	000205	RTS	R5	
153					
154	001360	005767	176420	PCHDTA: TST	PCHFLG :PUNCH ON?
155	001364	001463		BEO	P.FIN :NO
156	001366	011004		MOV	(R0).R4 :R4=#PASSES TO PUNCH
157	001370	001002		BNE	.+6
158	001372	012704	000003	MOV	#3,R4 :0==>ALL 3 PASSES
159	001376	005005		CLR	R5 :BYTE COUNT
160	001400	104400		IOWAIT	
161	001402	000003		HSP	
162	001404	012701	001636*	MOV	#PBUFS,R1 :START OF BUFFER
163	001410	005267	000350	INC	BLKCT
164	001414	116721	000344	MOVB	BLKCT,(R1)+ :MOVE BLOCK #
165	001420	110421		MOVB	R4,(R1)+ :MORE #PASSES THIS BLOCK
166	001422	062705	000002	ADD	#2,R5 :BYTE COUNT
167	001426	012702	000440*	MOV	#D.RSTG,R2 :↑ RATE STORAGE
168	001432	010403		MOV	R4,R3 :COUNT
169	001434	104007		P.MOVR: MOVF	:MOVE A RATE
170	001436	012021		MOV	(R2)+,(R1)+
171	001440	062705	000006	ADD	#6,R5
172	001444	005303		DEC	R3
173	001446	003372		BGT	P.MOVR
174	001450	012702	000462*	MOV	#D.DSTG,R2 :↑ D/A STORAGE
175	001454	010403		MOV	R4,R3
176	001456	012021		P.MOVD: MOV	(R2)+,(R1)+ :MOVE A D/A
177	001460	062705	000002	ADD	#2,R5
178	001464	005303		DEC	R3
179	001466	003373		BGT	P.MOVD
180	001470	005767	176312	TST	AUXFLG :AUXILLARY DATA WANTED?

131	001474	001412			BEQ	P.MFIN	:NO
182	001476	012702	000064*		MOV	#ALPHA,R2	:↑ AUX. DATA
183	001502	012703	000006		MOV	#6,R3	:6 DATA
184	001506	062705	000044		ADD	#36,,R5	:ADJUST BYTE COUNT
185	001512	104007			P.MOVX: MOVF		
186	001514	012321			MOV	(R2)+,(R1)+	
187	001516	005303			DEC	R3	
188	001520	003374			BGT	P.MOVX	
189	001522	010567	000106		P.MFIN: MOV	R5,PBCT	:EMPLACE BYTE COUNT
190	001526	000004			WRITE		
191	001530	001630*			PBUF		
192	001532	012	003		.BYTE	WRIC,HSP	
193	001534	000207			P.FIN: RTS	PC	
194							
195	001536	004767	000000G		RMTR: JSR	PC,ENCODE	:READ THE METER
196	001542	016767	000000G 000000G		MOV	DVMLO,DVM1	:SET UP
197	001550	016767	000000G 000000G		MOV	DVMHI,DVM2	:FOR BCDT0F
198	001556	004767	000000G		JSR	PC,BCDT0F	:CVRT TO FPN
199	001562	012700	000000G		MOV	#METER,R0	:↑
200	001566	012701	001734*		MOV	#FLAST,R1	:↑
201	001572	104004			MULF		
202	001574	016710	176214		MOV	D.M,(R0)	:METER*SCALE
203	001600	104001			ADDF		
204	001602	016710	176214		MOV	D.O,(R0)	:+OFFSET
205	001606	000207			RTS	PC	
206							
207	001610	000012			NULBUF: NBE-NBS		
208	001612	000003			3		
209	001614	000012			NBE-NBS		
210	001616	000000	000000 000000		NBS: .WORD	0,0,0,0,0	
	001624	000000	000000				
211	001630				NBE: .EVEN		
212	001630	000076			PBUF: PEE-PBUFS		
213	001632	000001			1		
214	001634	000000			PBCT: 0		
215	001636	001734*			PBUFS: .+,+62.		

ORIGINAL PAGE IS
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216	001734		PBE:	.EVEN	
217					
218	001734	001742'	FLAST:	.=.+6	
219	001742	001746'	D.SS:	.=.+4	
220	001745	001754'	RATE:	.=.+6	
221	001754	000000	MCOUNT:	.WORD	0
222	001755	000000	MNUM:	.WORD	0
223	001750	000000	NUMBER:	.WORD	0
224	001752	000000	COUNT:	.WORD	0
225	001754	000000	BLKCT:	.WORD	0
226	001755	000440' 000446' 000454'	RTBL:	.WORD	D.RSTG,D.RSTG+6.,D.RSTG+12.
227	001774	000130' 000136' 000144'	CTBL:	.WORD	C1,C2,C3
228	002002	000000G 000000G 000000G	PTBL:	.WORD	APASS1,APASS2,APASS3
229	002010	000003	D.3:	.WORD	3
230	002012	000006	D.6:	.WORD	6
231	002014	000000 000000 000000	F.0:	.WORD	0,0,0
232	002022	000000	DATMP:	.WORD	0
233		000001'		.END	

ORIGINAL PAGE IS
OF POOR QUALITY

APPASX

Calculates Rate Error from Rate Value

Calculates Controller Output

*Note: At the end of each pass a return from subroutine should be added.


```

1      ;
2      ; PDP-11 SELF-OPTIMIZING CONTROLLER
3      ;
4      ; REV: 6/19/74
5      ;
6      ; CONTENTS:
7      ;     1. APASS1
8      ;     2. APASS2
9      ;     3. APASS3
10     ;
11     ; THIS MODULE COMPUTES THE CONTROL VARIABLE, M,
12     ; GIVEN THE REFERENCE INPUT, CREF, AND THE SYSTEM
13     ; OUTPUT, C. IT ALSO COMPUTES THE FILTERED VARIABLES,
14     ; CBAR AND MBAR, AS WELL AS THE PSEUDO-CORRELATION
15     ; FUNCTIONS, PXXXX.
16     ;
17     ; CALLING CONVENTION:
18     ;
19     ;     JSR     PC,APASS<X>      ;<X>=1,2, OR 3
20     ;
21     .TITLE  APASSX
22     .CSECT
23     .GLOBL  APASS1,APASS2,APASS3
24
25     .GLOBL  CREF
26     .GLOBL  ALPHA,BETA
27     .GLOBL  A1,A2,B1,B2
28     .GLOBL  C1,C2,C3
29     .GLOBL  E1,E2,E3
30     .GLOBL  M1,M2,M3
31     .GLOBL  DASET
32
33     ; REGISTER ASSIGNMENTS
34
35     000000  R0      =      %0
36     000001  R1      =      %1

```

37	000002
38	000003
39	000004
40	000005
41	000006
42	000007
43	
44	177776
45	
46	
47	
48	104001
49	104002
50	104003
51	104004
52	104005
53	104006
54	104007
55	104010
56	104011
57	104012
58	104013
59	104014
60	104015
61	104016
62	104017
63	104020
64	104021
65	104022
66	104023
67	104024
68	104025
69	104026
70	104027
71	104030
72	104031

R2	=	%2
R3	=	%3
R4	=	%4
R5	=	%5
SP	=	%6
PC	=	%7

PS	=	177776
----	---	--------

: FPP-11 EMT CALLS

ADDF	=	EMT+1
SUBF	=	EMT+2
NEGF	=	EMT+3
MULF	=	EMT+4
DIVF	=	EMT+5
NORM	=	EMT+6
MOVF	=	EMT+7
CMPF	=	EMT+10
FIX	=	EMT+11
FIXD	=	EMT+12
FLT	=	EMT+13
FLTD	=	EMT+14
ITOA	=	EMT+15
JTOA	=	EMT+16
FTOA	=	EMT+17
ETOA	=	EMT+20
OTOA	=	EMT+21
ATOI	=	EMT+22
PTOF	=	EMT+23
ATOO	=	EMT+24
COS	=	EMT+25
SIN	=	EMT+26
ATAN	=	EMT+27
LOG	=	EMT+30
EXP	=	EMT+31

73	104032	SQRT	=	EMT+32
74	104033	MUL	=	EMT+33
75	104034	DIV	=	EMT+34
76				
77	000200	FAM	=	200
78	000100	PM	=	100

1			:
2			: APASS1 -- PASS 1 OF CONTROL ALGORITHM
3			:
4	000000		APASS1: ;JSR PC,APASS1
5			
6			: E1=CREF-C1 COMPUTE ERROR
7			
8	000000	104007	MOVF
9	000002	016740	MOV CREF,--(R0)
10	000005	104002	SUBF
11	000010	016710	MOV C1,(R0)
12	000014	104007	MOVF
13	000016	011067	MOV (R0),E1 ;LEAVE E1 ON STACK
14			
15			: M1=(E1-B1*E3+B1*E1)
16			
17	000022	104007	MOVF
18	000024	016740	MOV B1,--(R0)
19	000030	104004	MULF
20	000032	016710	MOV E3,(R0)
21	000036	104101	ADDF+PM
22	000040	104007	MOVF
23	000042	016740	MOV B2,--(R0)
24	000045	104004	MULF
25	000050	016710	MOV E1,(R0)
26	000054	104101	ADDF+PM
27	000058	104007	MOVF
28	000060	012067	MOV (R0)+,M1 ;POP M1
29			
30			: CALL DASET TO SET UP D/A CONVERTER
31			
32	000064	004567	JSR R5,DASET
33	000070	000000G	M1
34			
35			: END OF PASS 1 -- RETURN
36			

37 000072 000207

RTS PC


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1
2
3
4 000074
5
6
7
8 000074 104007          MOVF
9 000076 016740 000000G  MOV    CREF,-(R0)
10 000102 104002          SUBF
11 000104 016710 000000G  MOV    C2,(R0)
12 000110 104007          MOVF
13 000112 011067 000000G  MOV    (R0),E2          ;LEAVE E2 ON STACK
14
15
16
17 000116 104007          MOVF
18 000120 016740 000000G  MOV    B1,-(R0)
19 000124 104004          MULF
20 000126 016710 000000G  MOV    E1,(R0)
21 000132 104101          ADDF+PM
22 000134 104007          MOVF
23 000136 016740 000000G  MOV    B2,-(R0)
24 000142 104004          MULF
25 000144 016710 000000G  MOV    E2,(R0)
26 000150 104101          ADDF+PM
27 000152 104007          MOVF
28 000154 012067 000000G  MOV    (R0)+,M2          ;POP M2
29
30
31
32 000160 004567 000000G  JSR    R5,DASET
33 000164 000000G          M2
34
35
36
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37 003166 000207

RTS PC

ORIGINAL PAGE IS
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1					
2					
3					
4	000170			APASS3:	:JSR PC,APASS3
5					
6				: E3=CREF-C3	
7					
8	000170	104007		MOVF	
9	000172	016740	000000G	MOV	CREF.-(R0)
10	000176	104002		SUBF	
11	000200	016710	000000G	MOV	C3.(R0)
12	000204	104007		MOVF	
13	000206	011067	000000G	MOV	(R0).E3 :LEAVE E3 ON STACK
14					
15	000212	104007		MOVF	
16	000214	016740	000000G	MOV	B1.-(R0)
17	000220	104004		MULF	
18	000222	016710	000000G	MOV	E2.(R0)
19	000226	104101		ADDF+PM	
20	000230	104007		MOVF	
21	000232	016740	000000G	MOV	B2.-(R0)
22	000236	104004		MULF	
23	000240	016710	000000G	MOV	E3.(R0)
24	000244	104101		ADDF+PM	
25	000246	104007		MOVF	
26	000250	012067	000000G	MOV	(R0)+.M3 :POP M3
27					
28				: CALL DASET TO SET UP D/A CONVERTER	
29					
30	000254	004567	000000G	JSR	R5.DASET
31	000250	000000G		H3	
32					
33				: END OF PASS 3 -- RETURN	
34					
35	000262	000207		RTS	PC
36					

ADD

Stores D/A Values Between Samples

Sets Max/Min D/A Values

```

1      ; ADD ON VALUE OF CONTROLLER TO OBTAIN THE D/A
2      ; SETTING
3      ;
4      ;
5      ;
6      ; REV:          4/13/74
7      ;
8      ;
9      ; .TITLE  ADD
10     ; .GLOBL  ADD
11
12     ; .GLOBL  S.DA
13     ; .GLOBL  D.AMIN
14     ; .GLOBL  D.AMAX, TEMP, BEGIN, DASET
15     ; .CSECT
16
17     ;
18     ; REGISTER & ADDRESS ASSIGNMENT
19     ; PC      =      %7
20     ; R2      =      %2
21     ; DACTL   =      177522
22
23     ;
24     ;
25     ;
26 000000 016767 000000G 000075 ADD:  MOV  S.DA,D.AMAX
27 000006 052767 000100 000070 ADD  #100,D.AMAX
28 000014 016767 000000G 000066 MOV  S.DA,D.AMIN
29 000022 162767 000100 000060 SUB  #100,D.AMIN
30 000030 061267 000052 BEGIN: ADD  (R2),TEMP
31 000034 026767 000046 000042 CMP  TEMP,D.AMAX
32 000042 003404 BLE  LOOP1
33 000044 016767 000034 000034 MOV  D.AMAX,TEMP
34 000052 000407 SR  LOOP3
35 000054 026767 000026 000026 LOOP1: CMP  TEMP,D.AMIN
36 000052 003003 BGE  LOOP3

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37	000064	016767	000020	000014		MOV	D.AMIN,TEMP
38	000072	016712	000010		LOOP3:	MOV	TEMP,(R2)
39	000076	011237	177522			MOV	(R2),@#DACTL
40	000102	00A207				RTS	PC
41	000104	000000			D.AMAX:	.WORD	0
42	000106	000000			TEMP:	.WORD	0
43	000110	000000			D.AMIN:	.WORD	0
44		000001					.END

DACQ

Controls Multiplex Values for DMM

Commands Measurements

Conversion from BCD format to 3 Word Floating Point


```

1      ;
2      ; DATA ACQUISITION SYSTEM DRIVER
3      ;
4      ; REV: 7/25/73
5      ;
6      ; CONTENTS:
7      ;     1. DAQEVL
8      ;     2. DAQSUP
9      ;     3. SENCDE
10     ;     4. ENCODE
11     ;     5. BCDTOF
12     ;
13     ; THIS MODULE IMPLEMENTS CONTROL OF THE HP 2402A IDVM
14     ; AND THE HP 2911 CROSSBAR SCANNER SYSTEMS. ENTRY
15     ; DAQEVL DOES DATA CONVERSION FOR CHANNEL, FUNCTION, AND
16     ; RANGE ENCODING. ENTRY DAQSUP DOES THE ACTUAL SETUP OF
17     ; THE DEVICES. ENTRY SENCDE INITIATES A METER READING
18     ; AFTER WAITING FOR THE CROSSBAR SCANNER TO COMPLETE
19     ; CONNECTIONS. ENTRY ENCODE INITIATES A METER READING.
20     ; ENTRY BCDTOF CONVERTS THE BCD METER READING TO
21     ; FLOATING POINT.
22     ;
23     ; CALLING CONVENTION:
24     ;
25     ;     JSR     PC,<X>  ;<X>:=DAQEVL,DAQSUP,SENCDE,
26     ;                   ;ENCODE,BCDTOF
27     ;
28     ; VARIABLES:
29     ;
30     ; FUNC  (SWI) FUNCTION: 0=FREQUENCY, 1=RESISTANCE,
31     ;     2=VOLTAGE
32     ; RANGE (SWI) RANGE: 4=AUTORANGE, 5=.1V, 6=1V/1K,
33     ;     7=10V/10K, 8=100V/.1MEG, 9=10MEG, OTHER=1KV/1MEG
34     ; CHAN  (SWI) CHANNEL TO BE CONNECTED
35     ; DACQ1 (SWI) IDVM CONTROL BITS (OUTPUT OF DAQEVL)
36     ; DACQ2 (SWI) XBAR CONTROL BITS (OUTPUT OF DAQEVL)

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37      : DACQ3 (SWI) IDVM CONTROL BITS (INPUT TO DAQSUP)
38      : DACQ4 (SWI) XBAR CONTROL BITS (INPUT TO DAQSUP)
39      : DVMLO (SWI) LOW ORDER MEASUREMENT BITS
40      : DVMHI (SWI) HIGH ORDER MEASUREMENT BITS
41      : DVM1 (SWI) LOW ORDER MEASUREMENT BITS TO BCDTOF
42      : DVM2 (SWI) HIGH ORDER MEASUREMENT BITS TO BCDTOF
43      : METER (FPN) METER READING AFTER BCDTOF
44      :
45      .TITLE  DACQ
46      .CSECT
47      .GLOBL  DAQEVL,DAQSUP,SENCDE,ENCODE,BCDTOF
48      .GLOBL  FUNC,RANGE,CHAN,DACQ1,DACQ2,DVMLO,DVMHI
49      .GLOBL  DACQ3,DACQ4,DVM1,DVM2
50      .GLOBL  METER
51
52      .GLOBL  CTLM DX
53
54      000000  R0      =      %0
55      000001  R1      =      %1
56      000002  R2      =      %2
57      000003  R3      =      %3
58      000004  R4      =      %4
59      000005  R5      =      %5
60      000006  SP      =      %6
61      000007  PC      =      %7
62
63      177776  PS      =      177776
64
65      : FPP-11 EMT CALLS
66
67      104023  ATOF     =      EMT+23
68
69      000000  FPM      =      200
70      000100  PM       =      100
71
72      177522  SCNCTL   =      177522  :DEV2 OUT

```

73	177524	DVHI	=	177524	:DEV2 IN
74	177522	DVMCTL	=	177522	:DEV1 OUT
75	177524	DVLO	=	177524	:DEV1 IN
76	177524	CHIID	=	177524	:DEV0 IN
77					
78	000000	DEV0	=	0	
79	000001	DEV1	=	1	
80	000002	DEV2	=	2	

ORIGINAL PAGE IS
OF POOR QUALITY.

1	000000	000000	FUNC:	.WORD	0
2	000002	000000	RANGE:	.WORD	0
3	000004	000000	CHAN:	.WORD	0
4	000006	000000	DACQ1:	.WORD	0
5	000010	000000	DACQ2:	.WORD	0
6	000012	177777	DACQ3:	.WORD	-1
7	000014	000003	DACQ4:	.WORD	3
8	000016	000000	DVMHI:	.WORD	0
9	000020	000000	DVMLO:	.WORD	0
10	000022	000000	DVM1:	.WORD	0
11	000024	000000	DVM2:	.WORD	0
12	000026	000000 000000 000000	METER:	.WORD	0.0.0
13					
14					
15			; ENCODE FUNCTION, RANGE, & CHANNEL INFORMATION		
16					
17			; (1) EVALUATE FUNCTION		
18	000034		DAQEVL:		;JSR PC,DAQEVL
19	000034	016701 177740	MOV	FUNC,R1	;PICK UP FUNCTION
20	000040	012703 177777	MOV	#177777,R3	;RESET FOR DACQ1
21	000044	022701 000001	CMP	#1,R1	;1 IS RESISTANCE
22	000050	001003	BNE	FREQ	
23	000052	042703 000002	BIC	#2,R3	;SET UP OHMS
24	000056	000405	BR	DORANG	
25	000060	022701 000003	FREQ:	CMP	#0,R1 ;0 IS FREQUENCY
26	000064	001002	BNE	DORANG	;DEFAULT IS VOLTS
27	000066	042703 000001	BIC	#1,R3	;SET UP FREQ
28					
29			; (2) EVALUATE RANGE		
30					
31	000072	016701 177704	DORANG:	MOV	RANGE,R1 ;PICK UP RANGE
32	000076	022701 000004	CMP	#4,R1	;CHECK RANGE
33	000102	003015	BGT	STORP3	;OUT OF RANGE - DEFAULT 1KV/1MEG
34	000104	001003	BNE	NAR	;NOT AUTO RANGE, EITHER
35	000106	042703 002000	BIC	#2000,R3	;SET AUTO RANGE
36	000112	000411	BR	STORP3	

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OF POOR QUALITY

```

37 000114 022701 000011
38 000120 002406
39 000122 012702 000001
40 000126 005302
41 000130 005301
42 000132 001375
43 000134 040203
44 000136 010357 177644
45
46
47
48 000142 016701 177636
49 000146 002001
50 000150 005401
51
52
53
54 000310 000310
55 000152 162701 000310
56 000156 002375
57 000160 062701 000310
58 000164 005002
59 000166 012703 000230
60 000172 161301
61 000174 002403
62 000176 066302 000006
63 000202 000773
64 000204 061701
65 000206 005743
66 000210 001370
67 000212 005302
68 000214 010357 177570
69 000220 003207
70
71
72 000222 000000

```

```

NAR:  CMP #9.,R1      ;CHECK RANGE
      BLT STORR3      ;DEFAULT AGAIN
      MOV #1,R2       ;RANGE BIT
LEFT1: ASL R2          ;MOVE BIT LEFT ONE
      DEC R1
      BNE LEFT1       ;ENOUGH?
      BIC R2,R3        ;SET RANGE BIT
STORR3: MOV R3,DAC01   ;SET DVM1 WORD IN MEMORY

; (3) EVALUATE CHANNEL

      MOV  CHAN,R1     ;PICK UP CHANNEL
      BGE .+4
      NEG R1           ;MAKE POSITIVE IF NEGATIVE

; (4) CONVERT FROM BINARY TO BCD 8-4-2-1

      LIMIT=200.
PLUS:  SUB #LIMIT,R1   ;MODULO LIMIT
      BGE PLUS
      ADD #LIMIT,R1
      CLR R2           ;FOR RESULT
      MOV #LIST,R3     ;POINTER
SX:    SUB (R3),R1      ;COUNT DOWN
      BLT AX           ;THROUGH?
      ADD 6(R3),R2      ;NO, COUNT IT
      BR SX           ;AND TRY FOR ANOTHER
AX:    ADD (R3),R1      ;RESTORE
      TST -(R3)        ;MOVE POINTER, LOOK FOR ZERO
      BNE SX           ;NOT ZERO -- NEXT DECADE
      INC R2           ;RESET ON, START & STEP OFF
      MOV R2,DAC02     ;SAVE X-BAR CHANNEL INFO
      RTS  PC

; BINARY TO BCD CONVERSION TABLES
      WORD 0           ;FOR END OF PROG.

```


73	000224	000001			.WORD	1.
74	000226	000012			.WORD	10.
75	000230	000144			.WORD	100.
76	000232	000020	000400	010000	LIST:	20,400,10000 ;BCD 1,10,100 LEFT 4 BITS

1				: INITIATE MEASUREMENT PROCESS
2				
3	000240			DAQSUP: ;JSR PC,DAQSUP
4	000240	012703	177522	MOV #SCNCTL,R3 ;SET UP POINTERS
5	000244	012702	000510	MOV #S100U,R2
6	000250	004567	000000G	JSR R5,CTLMDX ;SET UP DEVICE
7	000254	000002		DEV2
8	000258	013746	177776	MOV @#PS,-(SP) ;SAVE STATUS
9	000262	012737	000340 177776	MOV #340,@#PS ;PRIO 7
10	000270	016713	177520	MOV DACQ4,@R3:SHOW TO X-SAR: CHAN & RESET
11	000274	004712		JSR PC,@R2
12	000278	052713	000002	BIS #2,@R3 ;TURN OFF RESET
13	000282	004712		JSR PC,@R2 ;WAIT TIL END OF RESET
14	000284	012713	000003	MOV #3,@R3 ;TURN OFF L.L. SET
15	000310	004712		JSR PC,@R2 ;FOR SAFETY
16	000312	005313		DEC @R3 ;SET START
17	000314	004712		JSR PC,@R2
18	000316	005213		INC @R3 ;TURN OFF START
19				;CHANNEL SHOULD BE SET IN 30 MS FOR GUARD
20				: +8 MS FOR HI-LO
21	000320	012637	177776	MOV (SP)+,@#PS ;RESTORE OLD STATUS
22	000324	004567	000000G	JSR R5,CTLMDX ;SET UP DEVICE
23	000330	000001		DEV1
24	000334	016737	177454 177522	MOV DACQ3,@#DVNCTL ;SET UP METER FCH/RANGE
25	000340	000207		RTS PC

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```

1
2
3 000342          : WAIT ON XBAR CONNECTION
4 000342 012704 000620
5 000345 004767 000136
6 000352 005304
7 000354 003374
8
9
10
11 000355          : ENCODE THE METER.
12 000355 012703 177522
13 000352 012702 177524
14 000356 012704 000000G
15 000372 004514
16 000374 000000
17 000376 013746 177776
18 000402 012737 000340 177776
19 000410 032712 040000
20 000414 001775
21 000416 004514
22 000420 000001
23 000422 042713 004000
24 000425 004767 000056
25 000432 052713 004000
26 000435 004514
27 000440 000000
28 000442 032712 040000
29 000445 001375
30 000450 032712 040000
31 000454 001775
32 000456 012637 177776
33 000458 004514
34 000464 000001
35 000466 012767 177524 177324
36 000474 004514

SENCD:          :JSR PC,SENCD
              MOV  #400.,R4          :40*100-US=40-MS
MLOOP: JSR      PC,S100U
              DEC   R4
              BGT   MLOOP

ENCODE:          :JSR PC,ENCODE
              MOV  #DVMCTL,R3        :SET UP POINTERS
              MOV  #CHNID,R2
              MOV  #CTLM DX,R4
              JSR   R5,R4            :SET UP DEVICE
              DEVO
              MOV  @#PS,-(SP)        :SAVE PS
              MOV  #340,@#PS        :PRIO 7
              BIT  #40000,R2        :MAKE SURE METER WILL
              BEQ  .-4              :ACCEPT ENCODE
              JSR   R5,R4            :SET UP DEVICE
              DEVI
              BIC  #4000,R3          :ENCODE
              JSR  PC,S100U
              BIS  #4000,R3          :BACK OFF
              JSR   R5,R4            :SET UP DEVICE
              DEVO
MEWAIT: BIT  #040000,R2 :STALL FOR METER.
              BNE  MEWAIT           :WAITING FOR DROP
REWAIT: BIT  #040000,R2 :LOOK FOR RECORD SIGNAL
              BEQ  REWAIT           :WAITING FOR RISE
              MOV  (SP)+,@#PS       :RESTORE STATUS
              JSR   R5,R4            :SET JP DEVICE
              DEVI
              MOV  @#DVLO,DVMILO    :GET MEASUREMENT
              JSR   R5,R4            :SET UP DEVICE

```

ORIGINAL PAGE IS
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37 000475 000002
 38 000500 013767 177524 177310
 39 000506 000207
 40
 41 000510 012705 000022
 42 000514 005305
 43 000516 003376
 44 000520 000207

DEV2
 MOV @#DVHI,DVHI ;BOTH WORDS
 RTS PC ;RETURN TO CALLER

S100U: MOV #18,R5 ;100-US STALL
 S100UL: DEC R5
 BGT S100UL
 RTS PC

1	000522	162706	000012	BCD TO F: SUB	#12, SP	: MAKE A PLACE
2	000526	010600		MOV	SP, R0	: FOR ASCII STRING
3	000530	016703	177270	MOV	DVM2, R3	: GET 1ST WORD
4	000534	004767	000566	JSR	PC, C.000	: CONVERT TO ASCII
5	000540	016703	177256	MOV	DVM1, R3	: GET 2ND WORD
6	000544	004767	000056	JSR	PC, C.000	: CONVERT TO ASCII
7	000550	012720	026505	MOV	#"E-, (R0)+	: PUT IN EXP. INDIC.
8	000554	016703	177244	MOV	DVM2, R3	: NOW FOR EXPONENT
9	000560	012705	000001	MOV	#1, R5	: ONE BCD DIGIT
10	000564	004767	000054	JSR	PC, C.001	: CONVERT EXP
11	000570	120227	000066	CMPB	R2, #6	: >6 IS OVERFLOW
12	000574	003403		BLE	, +10	: NO
13	000576	112760	000053	MOV	#'+, -2(R0)	: E+9 FOR OVERFLOW
14	000604	112710	000054	MOV	#'. , @R0	: PUT IN TERMINATOR
15	000610	010601		MOV	SP, R1	: SOURCE
16	000612	104023		ATOF		: CONVERT IT
17	000614	011167	177206	MOV	(R1), METER	: PROTOTYPE
18	000620	062706	000012	ADD	#12, SP	: GIVE BACK SPACE
19	000624	000207		RTS	PC	: RETURN TO USER
20						
21	000626	012705	000001	C.000: MOV	#1, R5	
22	000632	004767	000006	JSR	PC, C.001	
23	000636	005300		DEC	R0	: IGNORE 1ST BCD DIGIT
24	000640	012705	000003	MOV	#3, R5	: CONVERT OTHER 3
25	000644	005002		C.001: CLR	R2	: RESULT
26	000646	012704	000004	MOV	#4, R4	: 4 BITS
27	000652	006103		ROL	R3 ; <-	: GET A BIT
28	000654	006102		ROL	R2 ; I	: IN R2
29	000656	005304		DEC	R4 ; I	: 4 BITS
30	000660	003374		BGT	, -6 ; ->	: TOTAL
31	000662	062702	000060	ADD	#60, R2	: MAKE ASCII
32	000666	110220		MOV	R2, (R0)+	: PUT IN RESULT
33	000670	005305		DEC	R5	
34	000672	003364		BGT	C.001	
35	000674	000207		RTS	PC	
36						

CTLMDX

Controls Multiplexer Status

1		;		
2		;	DR-11A MULTIPLEXER/DEMULTIPLEXER CONTROLLER	
3		;		
4		;	REV: 8/3/73	
5		;		
6		;	CONTENTS:	
7		;	1. CTLMDX	
8		;		
9		;	THIS MODULE SWITCHES THE DR-11A AMONG THE	
10		;	SEVERAL DEVICES ATTACHED TO IT	
11		;		
12		;	CALLING CONVENTION:	
13		;		
14		;	JSR R5,CTLMDX	
15		;	.WORD <DEVICE #>	:<DEVICE #>:=0,1,2,3
16		;		
17			.TITLE CTLMDX	
18			.GLOBL CTLMDX	
19	000000		.CSECT	
20				
21	000000	R0	=	%0
22	000001	R1	=	%1
23	000002	R2	=	%2
24	000003	R3	=	%3
25	000004	R4	=	%4
26	000005	R5	=	%5
27	000006	SP	=	%6
28	000007	PC	=	%7
29	177776	PS	=	177776
30	000340	PRI07	=	340
31	177520	MDXCTL	=	177520
32	177522	DMXOUT	=	177522
33	177524	MUXIN	=	177524
34				
35	000000 010446	CTLMDX: MOV	R4,-(SP)	:SAVE REGISTERS
36	000002 010246	MOV	R2,-(SP)	

37	000004	010046			MOV	R0,-(SP)	
38	000006	012702	177520		MOV	#MDXCTL,R2	:↑DR11A CSR
39	000012	012500			MOV	(R5)+,R0	:GET NEW DEVICE #
40	000014	006300			ASL	R0	:SLOT #
41	000016	013746	177776		MOV	@#PS,-(SP)	:SAVE STATUS
42	000022	052737	000340	177776	BIS	#PRI07,@#PS	:SET UP PRI07
43	000030	052712	000001		BIS	#1,(R2)	:LATCH IT UP
44	000034	011204			MOV	(R2),R4	:GET CURRENT DEVICE
45	000036	042704	177771		BIC	#177771,R4	:CLEAN IT UP
46	000042	012264	000102'		MOV	(R2)+,MCSTOR(R4)	:SAVE CURRENT CSR
47	000046	011264	000112'		MOV	(R2),MDSTOR(R4)	: AND CURRENT DATA
48	000052	016012	000112'		MOV	MDSTOR(R0),(R2)	:REPLACE W/ OLD DATA
49	000056	016042	000102'		MOV	MCSTOR(R0),(R2)	: AND OLD CSR
50	000062	042712	000001		BIC	#1,(R2)	:UNLATCH THE SWITCHES
51	000066	012637	177776		MOV	(SP)+,@#PS	:RESTORE PS
52	000072	012600			MOV	(SP)+,R0	:RESTORE REGS
53	000074	012602			MOV	(SP)+,R2	
54	000076	012604			MOV	(SP)+,R4	
55	000100	000205			RTS	R5	:RETURN
56	000102	000001	000003	000005	MCSTOR: .WORD	1,3,5,7	:PLACE FOR CSRS
	000110	000007					
57	000112	000000	000000	000000	MDSTOR: .WORD	0,0,0,0	:PLACE FOR DATA
	000120	000000					
58		000001'			.END		

POWER FAIL

Stores Working Register on Power Loss

Resets Hardware to Status Prior to Power Loss
on Power Up

Restores Working Registers on Power Up

1					
2			:		
3			:	POWER FAIL/RESTART ROUTINE	
4			:		
5			:	REV: 7/30/73	
6			:		
7			:	CONTENTS:	
8			:	1. PFAIL	
9			:		
10			:	THIS MODULE PROVIDES POWER FAILURE AND POWER RESTART	
11			:	CAPABILITIES FOR THE CONTROLLER PROGRAM. IT RESTORES	
12			:	AND SAVES ALL PERTINENT STATUS REGISTERS. I/O IN	
13			:	PROGRESS AT TIME OF POWER FAIL MAY SUFFER DROPPED	
14			:	DATA. THE D/A CONVERTER IS RESTORED ON POWER UP.	
15			:		
16			:	VARIABLES:	
17			:		
18			:	NPF (SWI) COUNT OF NUMBER OF POWER FAILURES	
19			:	PFLAG (SWI) FLAG: 0=POWER DOWN, -1=POWER UP	
20			:	SAVESP(SWI) STORAGE FOR STACK POINTER DURING PWR. OFF	
21			:		
22				.TITLE PFAIL	
23				.GLOBL NPF	
24					
25				.GLOBL CTLMX,DAQSUP	
26	000000		DEV0	=	0
27	177520		MDXCTL	=	177520
28	177522		DMXOUT	=	177522
29	177560		TKS	=	177560
30	177564		TPS	=	177564
31	177550		PRS	=	177550
32	177554		PPS	=	177554
33					
34			:	REGISTER ASSIGNMENTS	
35					
36	000000		R0	=	%0

```

37      000001
38      000002
39      000003
40      000004
41      000005
42      000006
43      000007
44
45      177776
46
47      000000
48      000024
49 000024 000006
50 000026 000340

```

```

R1      =      %1
R2      =      %2
R3      =      %3
R4      =      %4
R5      =      %5
SP      =      %6
PC      =      %7

PS      =      177776

```

```

.ASECT
=      24      :POWER FAIL VECTOR
PFAIL
340

```

1	000000			.CSECT		
2	000000	000000		NPF:	.WORD	0
3	000002	000000		PFLAG:	.WORD	0
4	000004	000000		SAVE\$P:	.WORD	0
5						
6	000006	005767	177770	PFAIL:	TST	PFLAG ;UP OR DOWN?
7	000012	001031			BNE	PUP ;UP..
8	000014	010546			MOV	R5,-(SP)
9	000016	010446			MOV	R4,-(SP)
10	000020	010346			MOV	R3,-(SP)
11	000022	010246			MOV	R2,-(SP)
12	000024	010146			MOV	R1,-(SP)
13	000026	010046			MOV	R0,-(SP)
14	000030	013746	177564		MOV	@#TPS,-(SP)
15	000034	013746	177560		MOV	@#TKS,-(SP)
16	000040	013746	177550		MOV	@#PRS,-(SP)
17	000044	013746	177554		MOV	@#PPS,-(SP)
18	000050	013746	177520		MOV	@#MDXCTL,-(SP)
19	000054	004567	000000G		JSR	R5,CTLMDX
20	000060	000000			DEV0	;SAVE ALL DEVICES
21	000062	010667	177716		MOV	SP,SAVE\$P ;SAVE THE STACK
22	000066	012767	177777 177706		MOV	#-1,PFLAG ;FLAG FOR UP
23	000074	000000			HALT	;WHOA..
24						
25	000076	016706	177702	PUP:	MOV	SAVE\$P,SP
26	000102	005067	177674		CLR	PFLAG
27	000106	012737	000004 177520		MOV	#4,@#MDXCTL ;RESTORE XBAR
28	000114	012737	000003 177522		MOV	#3,@#DMXOUT ;RESET OFF
29	000122	004567	000000G		JSR	R5,CTLMDX ;RESTORE D/A
30	000126	000000			DEV0	
31	000130	004767	000000G		JSR	PC,DAGSUP ;RESTORE DACQ
32	000134	011601			MOV	(SP),R1 ;GET OLD DEV
33	000136	042701	177771		BIC	#177771,R1 ;CLEAN UP
34	000142	006201			ASR	R1 ; GET INTO SHAPE
35	000144	010167	000004		MOV	R1,PU.01 ;AND INTO PLACE
36	000150	004567	000000G		JSR	R5,CTLMDX ;RESTORE DEVICE AT PDOWN

37	000154	000000		PU.01:	.WORD	0		:DEVICE # HERE
38	000156	012637	177520		MOV	(SP)+,@#MDXCTL		:FINISH
39	000162	012637	177554		MOV	(SP)+,@#PPS		
40	000166	012637	177550		MOV	(SP)+,@#PRS		
41	000172	012637	177560		MOV	(SP)+,@#TKS		
42	000176	012637	177564		MOV	(SP)+,@#TPS		
43	000202	012600			MOV	(SP)+,R0		
44	000204	012601			MOV	(SP)+,R1		
45	000206	012602			MOV	(SP)+,R2		
46	000210	012603			MOV	(SP)+,R3		
47	000212	012604			MOV	(SP)+,R4		
48	000214	012605			MOV	(SP)+,R5		
49	000216	005267	177556		INC	NPF		:COUNT THE FAILURE
50	000222	000002			RTI			:RESUME PROCESSING
51								
52		000001			.END			

APPENDIX C

The following computer program written in BASIC was used to plot and statistically analyze the data obtained during a digitally controlled deposition. Similar in capability to the program presented in Appendix A, this software package does not have the ability to monitor the deposition parameters as did the above material.

```

01 REM...PROGRAM TO PLOT CONTROLLER OUTPUT
02 REM...OPTIONS REQ: H,0      11/2/74
10 DIM R(240),D(240)
15 GOTO 500
50 LET U1=0
55 LET U=EXF(4,0)
60 IF U=0 THEN 100
65 FOR I=1 TO U
68 IF U1=240 THEN 100
70 LET U1=U1+1
75 LET R(U1)=EXF(4,I):LET D(U1)=EXF(4,I+3)
80 NEXT I
85 GOTO 55
100 LET Y2=9999/40:LET X2=9999/240
110 LET P=EXF(25,0,R1*Y2)+EXF(24,1)+EXF(26,9999,0)+EXF(24,0)
115 LET Y=R(4)*Y2:LET X=4*X2
120 IF Y>9999 THEN LET Y=9999
125 IF Y<0 THEN LET Y=0
130 LET P=EXF(25,X,Y)+EXF(24,1)
140 FOR I=5 TO U1
150 LET Y=R(I)*Y2:LET X=I*X2
155 IF Y>9999 THEN LET Y=9999
160 IF Y<0 THEN LET Y=0
165 LET P=EXF(25,X,Y)
170 NEXT I
175 LET P=EXF(24,0)
190 PRINT"INPUT MAX D/A SETTING...IF UNKNOWN ENTER 0";:INPUT H
195 IF H<>0 THEN 220
200 LET H=1E-6
205 FOR I=4 TO U1
210 IF D(I)>H THEN LET H=D(I)
215 NEXT I
216 PRINT"MAX D/A SETTING="H"ENTER DESIRED VALUE";:INPUT H
220 LET L=H-200
225 PRINT"INSTALL RED PEN & <CR> TO BEGIN";:INPUT A2
230 LET X3=9999/240:LET Y3=9999/200
235 LET X2=4*X3:LET Y2=(D(4)-L)*Y3
240 IF Y2>9999 THEN LET Y2=9999
245 IF Y2<0 THEN LET Y2=0
250 LET P=EXF(25,X2,Y2)+EXF(24,1)
255 FOR I=5 TO U1
256 IF I>240 THEN 300
260 IF D(I)=D(I-3) THEN 295
265 LET X=I*X3:LET Y=(D(I)-L)*Y3
270 IF Y>9999 THEN LET Y=9999
275 IF Y<0 THEN LET Y=0
280 LET Y4=Y-Y2:LET Y2=Y
285 LET X4=X-X2:LET X2=X
290 LET P=EXF(26,X4,0)+EXF(26,0,Y4)
295 NEXT I
300 LET P=EXF(24,0)
305 PRINT"INPUT STATISTICAL RANGE";:INPUT L2,U2
310 LET R5=U2-L2+1:LET R6=0:LET R7=0:LET R8=0

```



```

315 FOR I=L2 TO U2
320 LET R6=R(I)*R(I)+R6
325 LET R7=R(I)+R7
330 NEXT I
335 LET M=R7/R5
340 FOR I=L2 TO U2
345 LET R8=ABS(R(I)-M)+R8
350 NEXT I
355 LET R8=R8/(R5-1)
360 LET S=SQR((R6-(R7^2/R5))/(R5-1))
365 GOTO 530
385 PRINT"DATE & #";:INPUT M1,D1,Y1,N1
390 PRINT"MATERIAL";:INPUT T1
395 PRINT"RATE";:INPUT R1
400 PRINT"INSTALL BLUE PEN & <CR> TO BEGIN";:INPUT A1
405 LET P=EXF(24,0)+EXF(25,0,0)+EXF(24,1)
410 FOR I=1 TO 3
415 LET P=EXF(26,2500,0)+EXF(26,0,100)+EXF(26,0,-100)
420 NEXT I
425 LET P=EXF(25,9999,0)
430 FOR I=1 TO 3
435 LET P=EXF(26,0,2500)+EXF(26,-100,0)+EXF(26,100,0)
440 NEXT I
445 LET P=EXF(25,9999,9999)
450 FOR I=1 TO 3
455 LET P=EXF(26,-2500,0)+EXF(26,0,-100)+EXF(26,0,100)
460 NEXT I
465 LET P=EXF(25,0,9999)
470 FOR I=1 TO 3
475 LET P=EXF(26,0,-2500)+EXF(26,100,0)+EXF(26,-100,0)
480 NEXT I
485 LET P=EXF(25,0,0)+EXF(24,0)
490 GOTO 50
500 PRINT"INPUT DATE OF DEPOSITION...M,D,Y";:INPUT M1,D1,Y1
505 PRINT"INPUT RUN NUMBER...";:INPUT N1
510 PRINT"INPUT TYPE MATERIAL...KEY";
512 PRINT"    1-CHROMIUM,2-SILVER,3 TIN SELENIDE";
515 INPUT T1
520 PRINT"INPUT DESIRED RATE...";:INPUT R1
525 GOTO 400
530 PRINT:PRINT:PRINT:PRINT
535 PRINT"TEST DATE..."M1"/"D1"/"Y1"#"N1
540 PRINT"DEPOSITION MATERIAL..."";
545 IF T1=1 THEN PRINT"CHROMIUM"
550 IF T1=2 THEN PRINT"SILVER"
555 IF T1=3 THEN PRINT"TIN SELENIDE"
560 PRINT"DEPOSITION MADE IN NRC VACUUM SYSTEM"
570 PRINT"X AXIS SCALED 0 TO 240 (SECS)"
575 PRINT"STATISTICAL RANGE "L2"TO"U2
580 PRINT"STANDARD DEVIATION "S
585 PRINT"MEAN DEVIATION "R8
590 PRINT"MEAN VALUE "M
595 PRINT"RATE AXIS (BLUE) SCALED 0 TO 40"
600 PRINT"D/A AXIS (RED) SCALED"L"TO"L+200
605 PRINT:PRINT:PRINT:PRINT
610 GOTO 385

```

APPENDIX D

The following served as a guide to assist a person nonfamiliar with the execution of the digital controllers software package. It does require familiarization with the digital processor and associated peripheral hardware. The peripheral hardware not only includes items such as the high speed reader/punch, data acquisition unit and digital plotter, but also requires a working knowledge of the vacuum system, SCR power controller, and other vacuum deposition hardware.

Not included in the procedure for execution of the controller program is the technique used to obtain a suitable value for the Final Rise value. This value can be determined experimentally with the aid of the digital controller software package.

By inputting a large soak time such as a 1000 seconds, a small rise time such as 10 seconds, and a Final Rise smaller than required for deposition, the system will quickly reach the soak level. Once in the soak mode, the value of the soak setting can be incremented via the teletype and the command "LET SOAK POWER=". Incrementing the soak power until a deposition rate is obtained and reducing the value until the rate ceases will result in a Final Rise value equal to the Soak Power setting.

PROCEDURE FOR EXECUTING CONTROLLER PROGRAM

- 1) Load Controller Program with absolute loader at address 037500. (137500 if full memory capability exists)
- 2) Program will load and have the following response to which you will reply thusly:

Computer	Operator	Remarks
* 000000	21472/ 1 or 4 (CR)	The sample rate 1-SnSe and other low conductivity substances; 4-Ag and other metals
*	14006;G	Starts Controller Program

- 3) Once in the controller program, the following variables need to be input:
 - a. RATE SET
 - b. Initial Rise
 - c. Final Rise
 - d. Rise Time - in seconds
 - e. Soak Time - in seconds
 - f. Deposit Time - in seconds
 - g. Max Power
 - h. Min Power
 - i. B2
 - j. Punch On - If punch isn't desired, no input is required
- 4) To input a variable, strike a "CTRL P" (↑P) and the computer will respond with a colon (:). At that time, similar to BASIC, input LET variable (a-j) = value. For punch routine, poll the computer and type PUNCH ON.
- 5) Choices on the above variables can be based on the following criteria:

$$\text{Initial Rise} = \frac{\text{Final Rise}}{\text{Rise Time}}$$

$$\text{Max Power} = \frac{\text{RATE SET}}{4}$$

$$\text{Min Power} = - \frac{\text{RATE SET}}{4}$$

$$\text{B2} = 4$$

- 6) To start program, poll the computer and type GO.
- 7) For Emergency Stop, poll the computer and input X.
- 8) Other features that might be of interest are the variables that can be requested to be printed on the teletype. Along with the above variables, Sect 3, the following variables can be polled.
 - a. CST - Current Soak Time
 - b. CRT - Current Rise Time
 - c. CDT - Current Deposit Time
 - d. RATE - Current Rate being monitored
 - e. CRP - Current Rise Power
 - f. CSP - Current Soak Power
 - g. CDP - Current Deposition Power
 - h. SOAK Power - Current Soak Power (used to change the soak value)
- 9) In case the soak power is too high or soak time is too long, the deposition process can be initiated at any time once the soak level has been reached by polling the computer and inputting DEPOSIT.
- 10) Once deposition phase has been initiated, it might be desired to set the computer to deposit only a certain thickness of material. To accomplish this task, poll the computer and type LET THICKNESS - "value." Upon striking return, the computer will take its present frequency value, add the value entered, and then stop the process once the combined frequency is reached.
- 11) Any of the above variables can be changed at any time by polling the computer and inputting the new value.
- 12) In order to change the Sample Time, poll the computer and input DEBUG. This puts the program back in the state it was in at the beginning of the program. Change the one address (21472) to the desired sample rate. Then return to the controller program with 14006;G. All of the variables that had previously been set have remained unchanged during the sample time change; thus, no initialization is required.
- 13) Following is a table that depicts values for variables that have been found to work reliably on the NRC System:

	Ag	SnSe
Sample Time	4	1
Initial Rise	270	240
Final Rise	470	440
Rise Time	51	100
Soak Time	100	25
B2	4	4

- 14) Following is a sample listing for silver being deposited at a desired rate of 10 Hz/sec:

*21472/000000 4 (CR)

*14006;G (CR)

:LET RATE SET = 10

:LET INITIAL RISE = 270

:LET FINAL RISE=470

:LET RISE TIME=51

:LET SOAK TIME=100

:LET DEPOSIT TIME=240

:LET MAX POWER=2.5

:LET MIN POWER=-2.5

:LET B2=4

:PUNCH ON

:GO

DEPOSITION COMPLETED

APPENDIX E

Since statistical data, especially the mean and standard deviation, have meaning only if the sample data can be considered as part of a normal distribution, it is necessary to evaluate a typical run to determine if the rate data are part of a normal distribution. Also before a statistical analysis has meaning, the parameter of interest has to demonstrate that it is random in nature; that is, it is aperiodic about the mean value.

Figure E.1 illustrates a typical run which shows both the rate and the D/A settings plotted as a function of time. Disregarding the transient portion of the curve and only evaluating that portion which appears to have become stable, correlation analysis of the data yielded a constant value for all correlation factors from one second to fifty seconds. For the data no periodicity exists that can be measured numerically. This means the rate can be considered to be random about the mean value.

The next hypothesis, to check the statistical behavior of the rate data, is the determination of the distribution of the data about the mean. Separating the data shown into classes which portray the number of rate samples in a given rate interval, a histogram of the rate data, Fig. E.2, can be constructed. By connecting the center points of each class by a smooth line, a distribution function for the rate data can be illustrated. Using (E.1) below and the calculated mean and standard deviation, a normal distribution curve can be plotted along

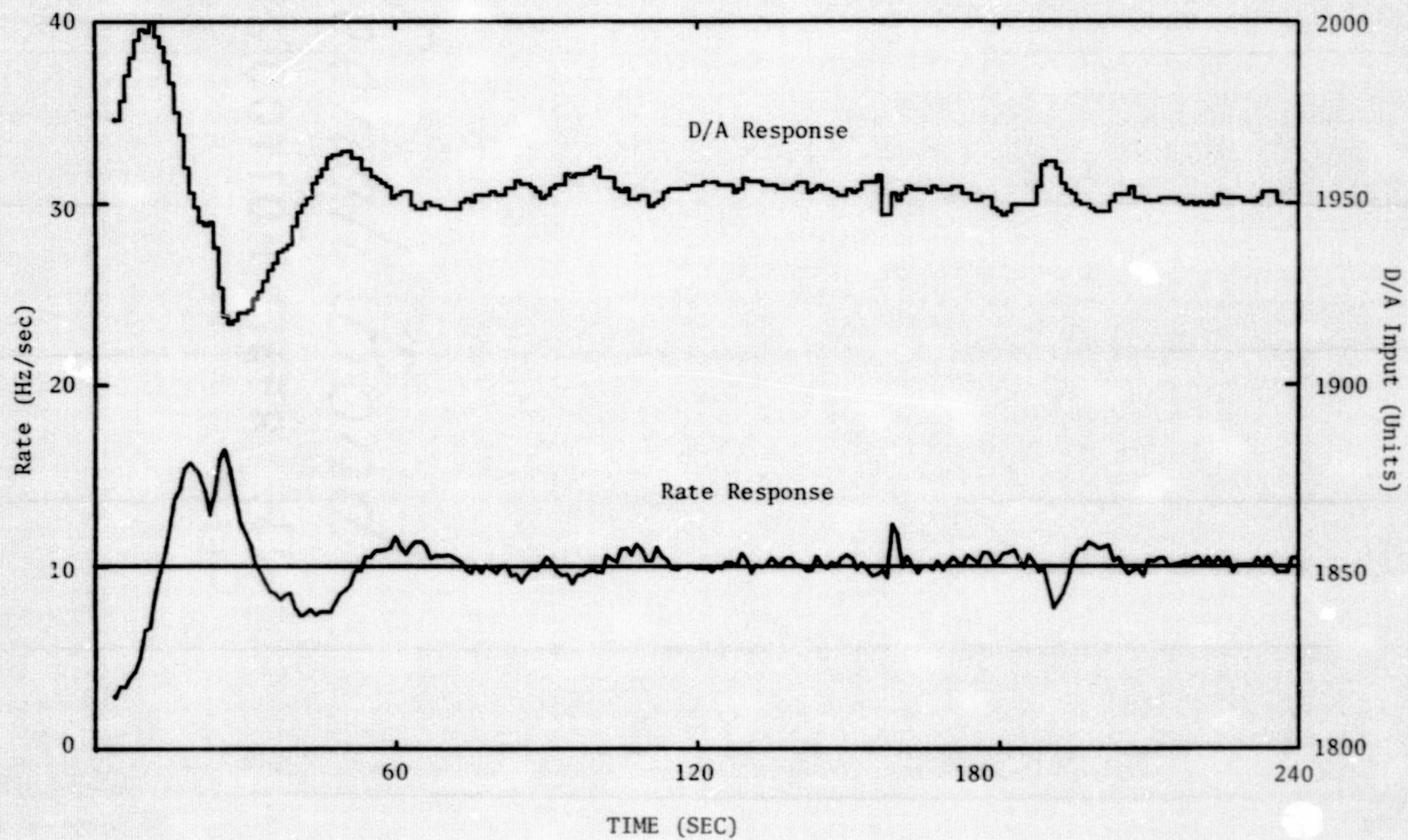


Figure E.1. A Typical Deposition Response

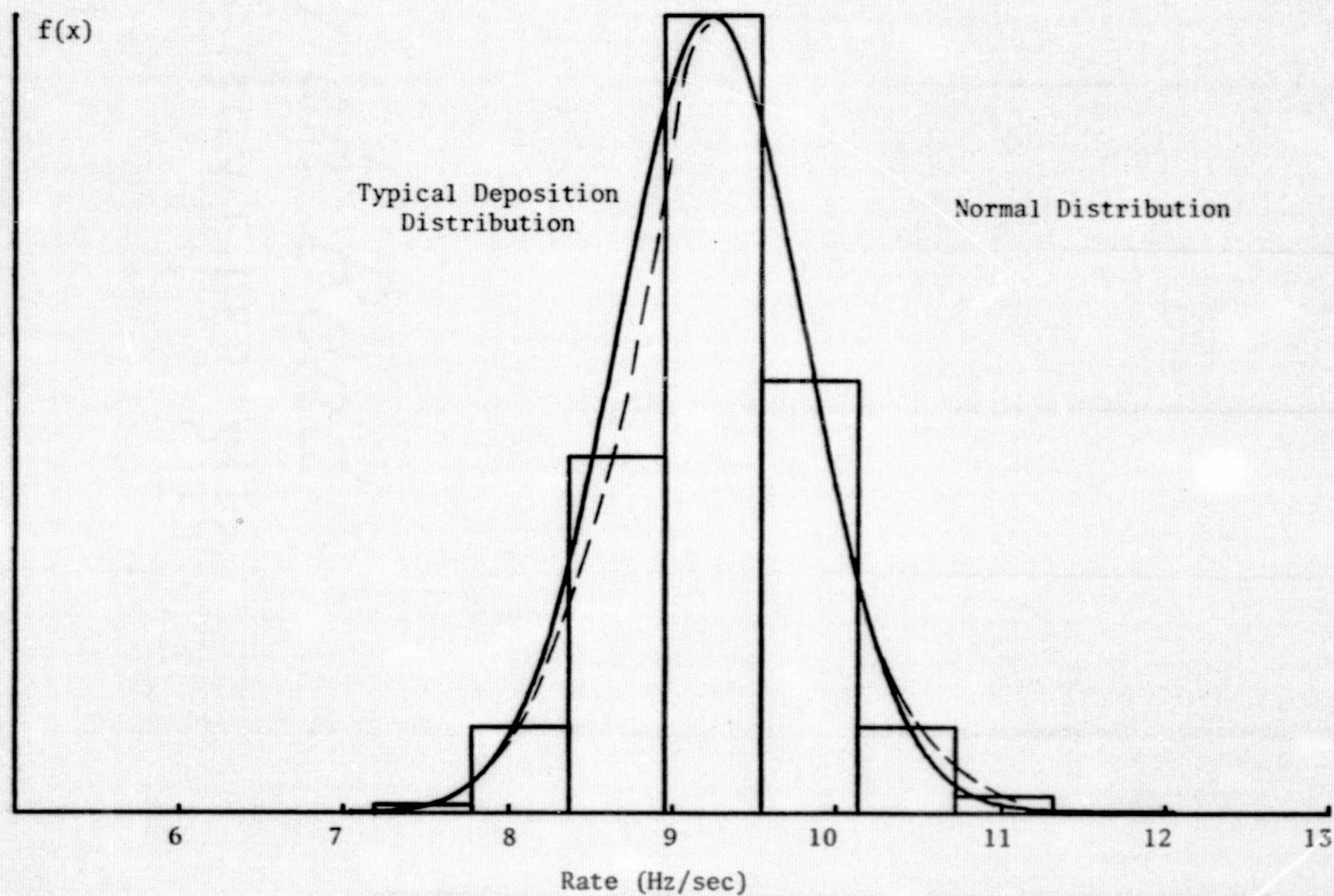


Figure E.2. Histogram and Distribution Curve Versus A Normal Distribution for a Typical Deposition Run

with the distribution curve obtained from the histogram. This showed that the rate data can be represented meaningfully by statistical measurements.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-1/2\left(\frac{x-\mu}{\sigma}\right)^2} \quad (E.1)$$

where $f(x)$ = the normal distribution function about the mean μ and standard deviation σ ,

μ = mean, and

σ = standard deviation.

Thus, it has been shown that the statistical parameters obtained from the rate data are valid.

APPENDIX F

The following graphs illustrate the variation of the velocity multiplier versus achieved mean standard deviation for the various sample time. Each graph represents a given material deposited at a given rate.

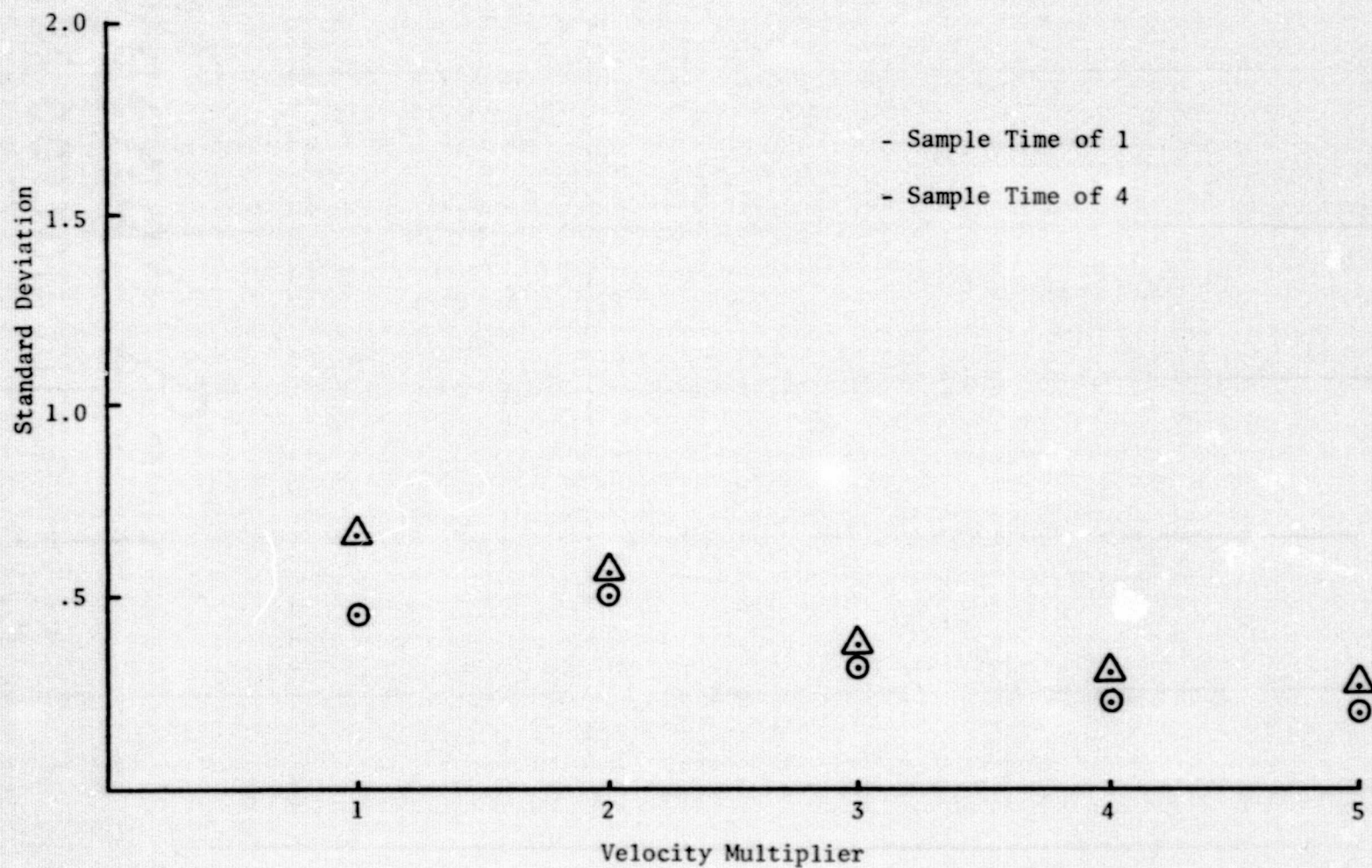


Figure F.1. Standard Deviation versus Velocity Multiplier for Silver Deposited at One Hertz/Sec

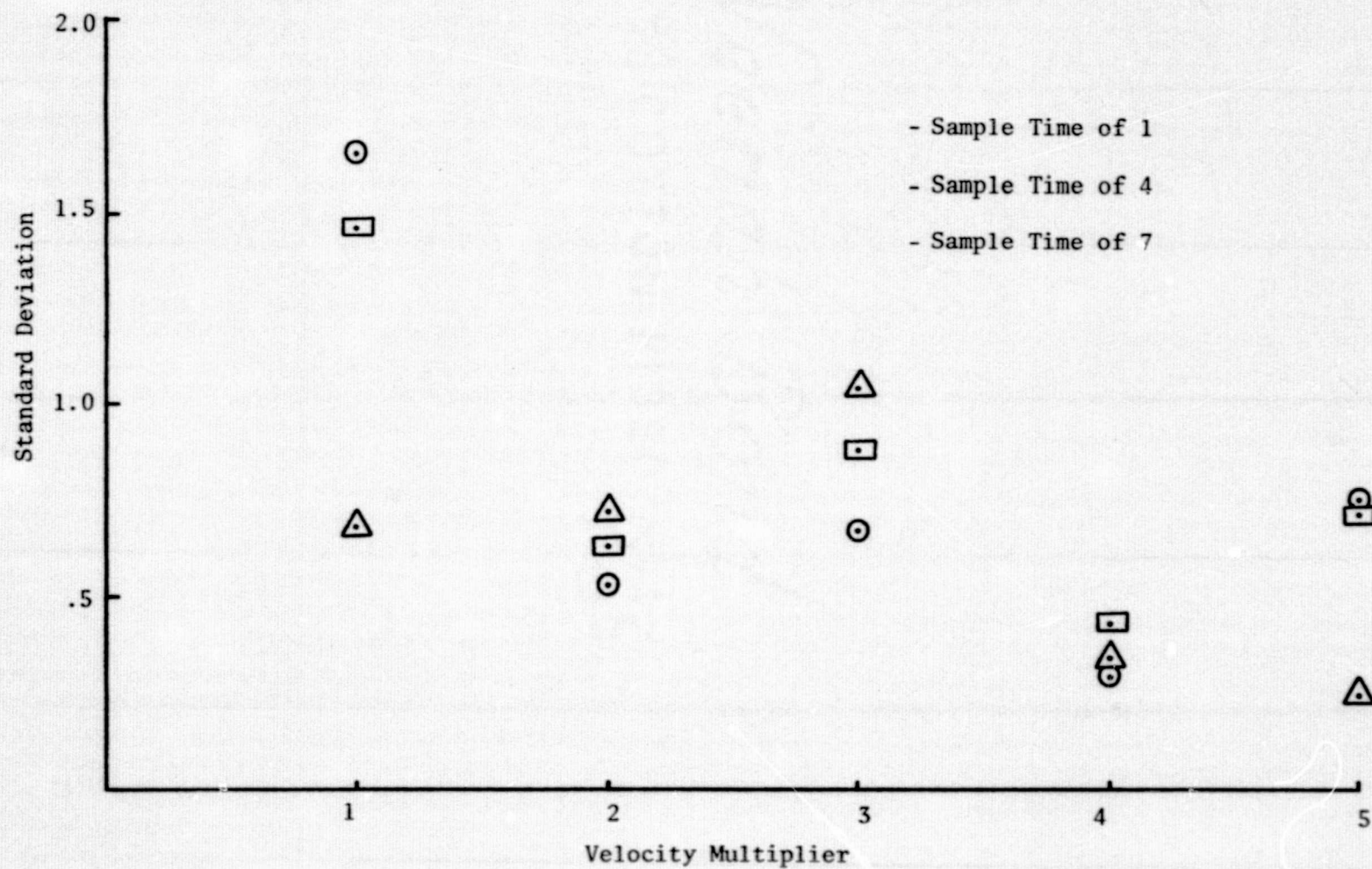


Figure F.2. Standard Deviation versus Velocity Multiplier for Silver Deposited at Five Hertz/Sec

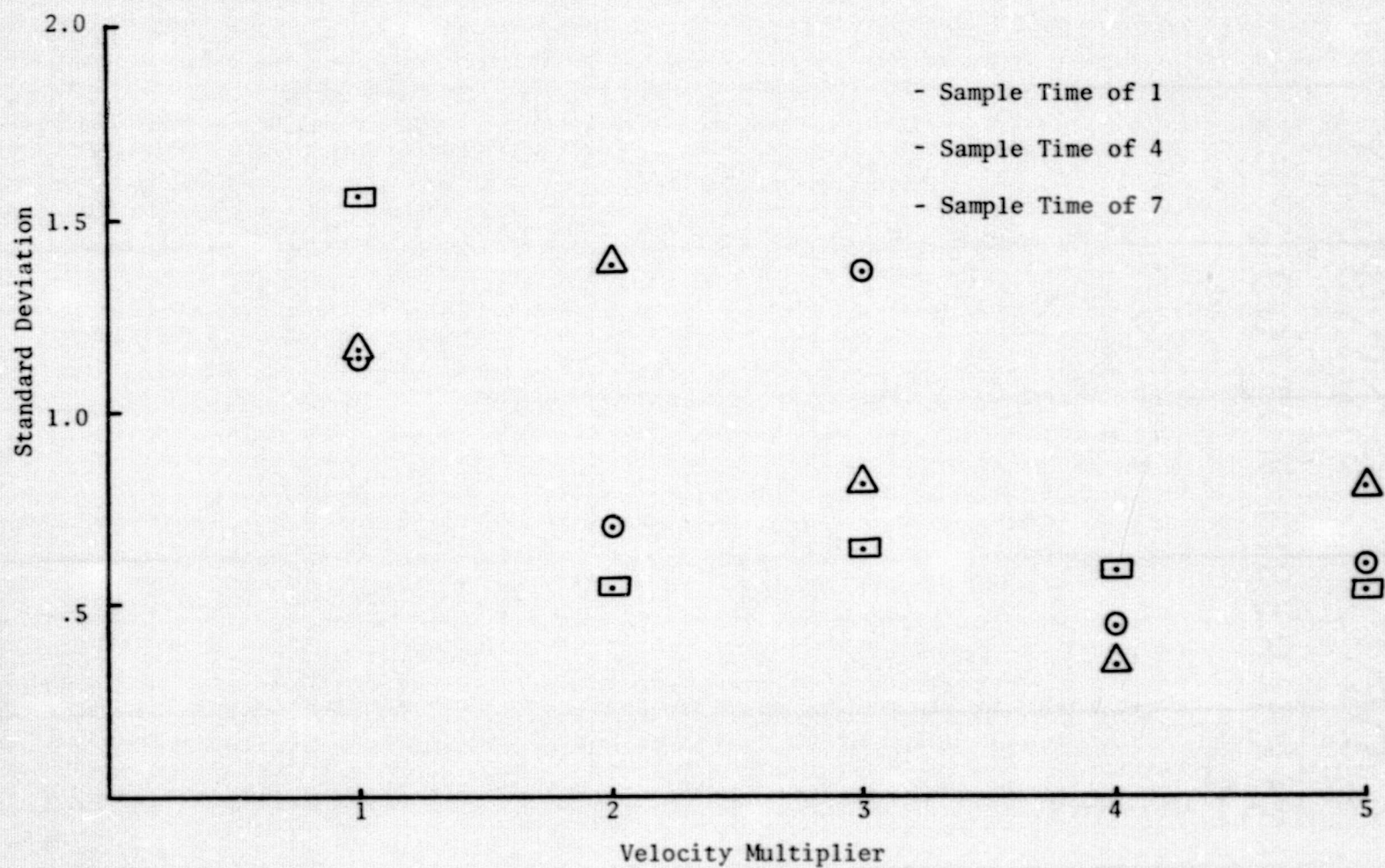


Figure F.3. Standard Deviation versus Velocity Multiplier for Silver Deposited at Ten Hertz/Sec

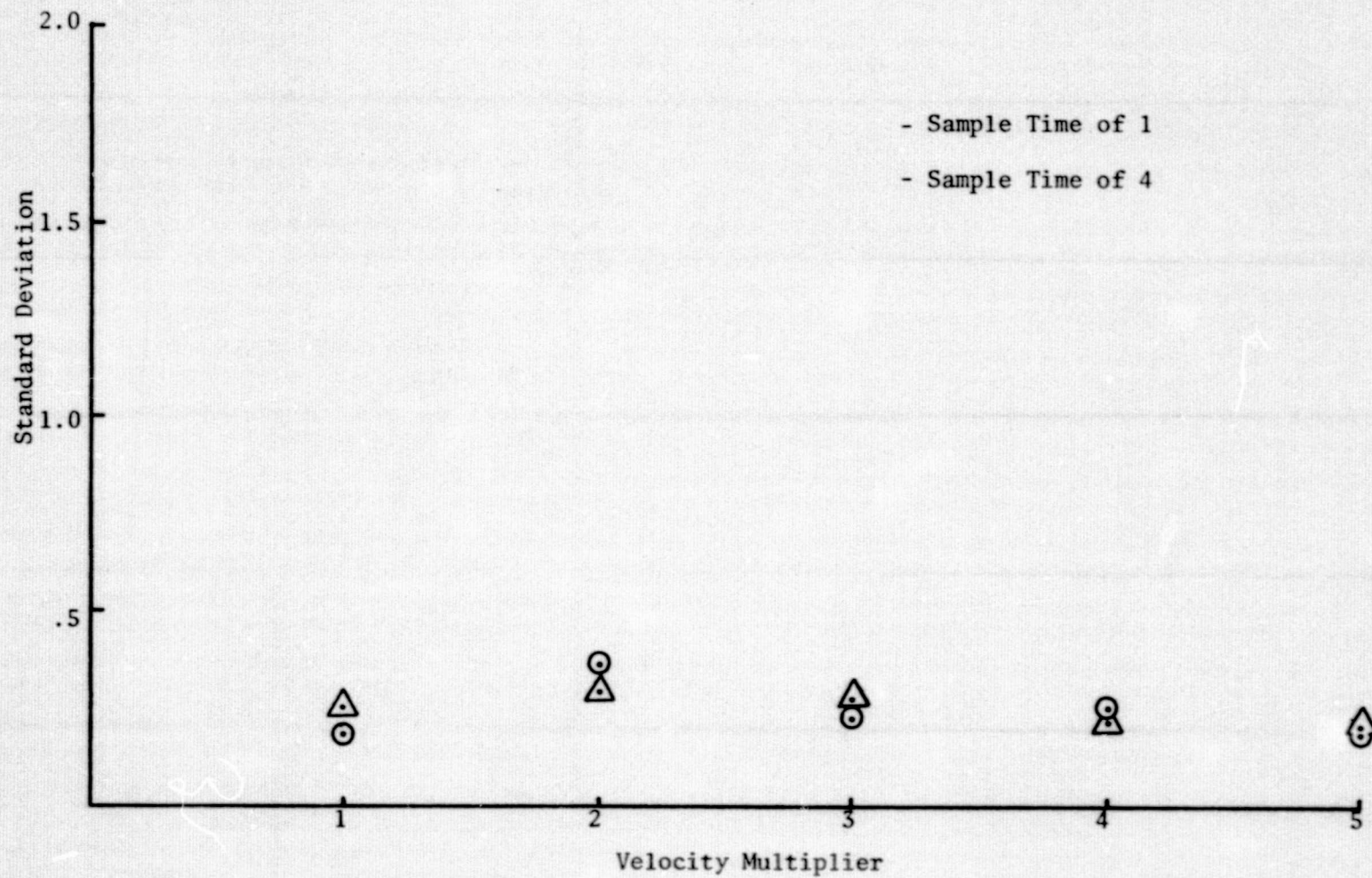


Figure F.4. Standard Deviation versus Velocity Multiplier for Tin Selenide Deposited at One Hertz/Sec

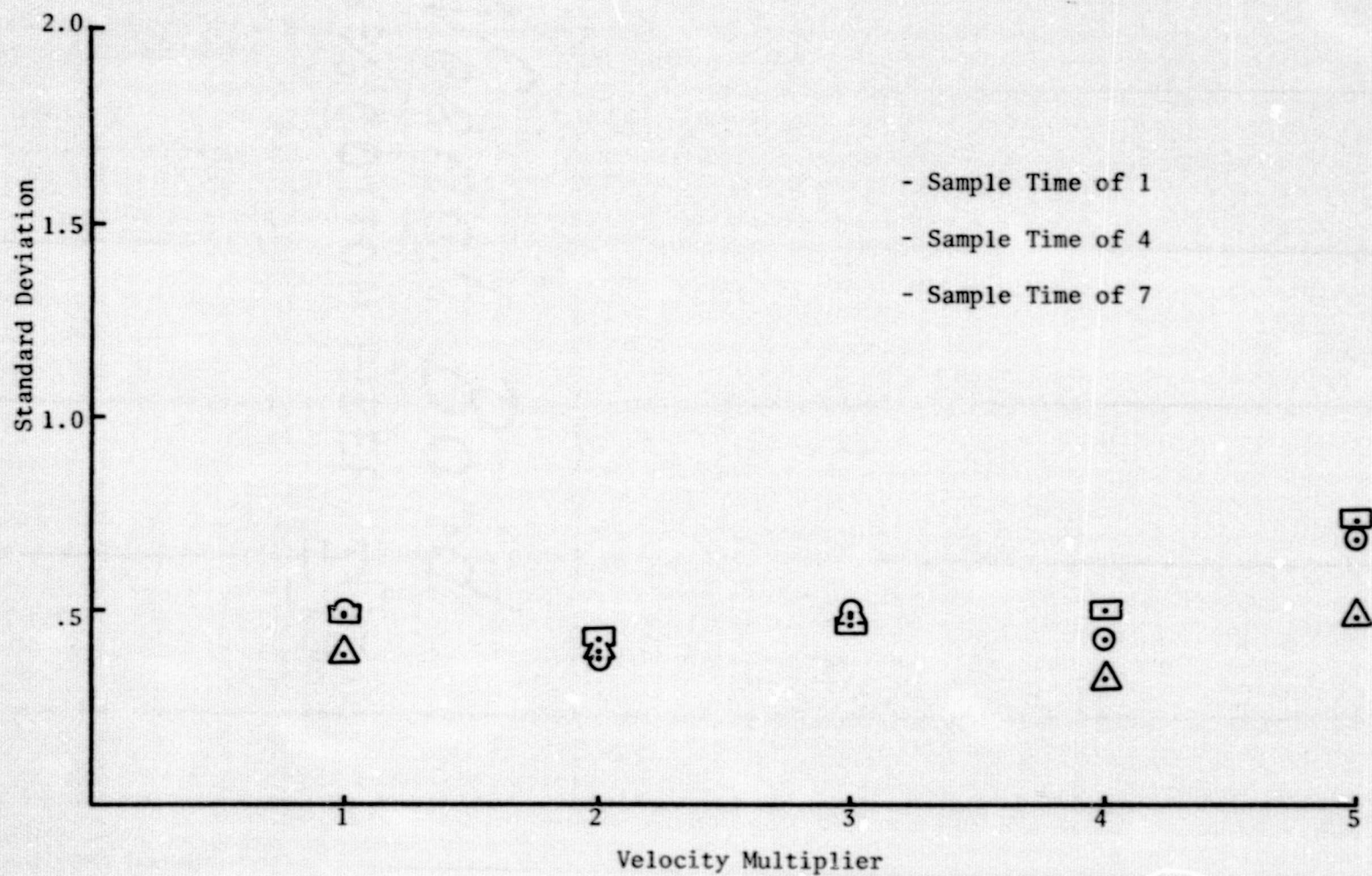


Figure F.5. Standard Deviation versus Velocity Multiplier for Tin Selenide Deposited at Five Hertz/Sec

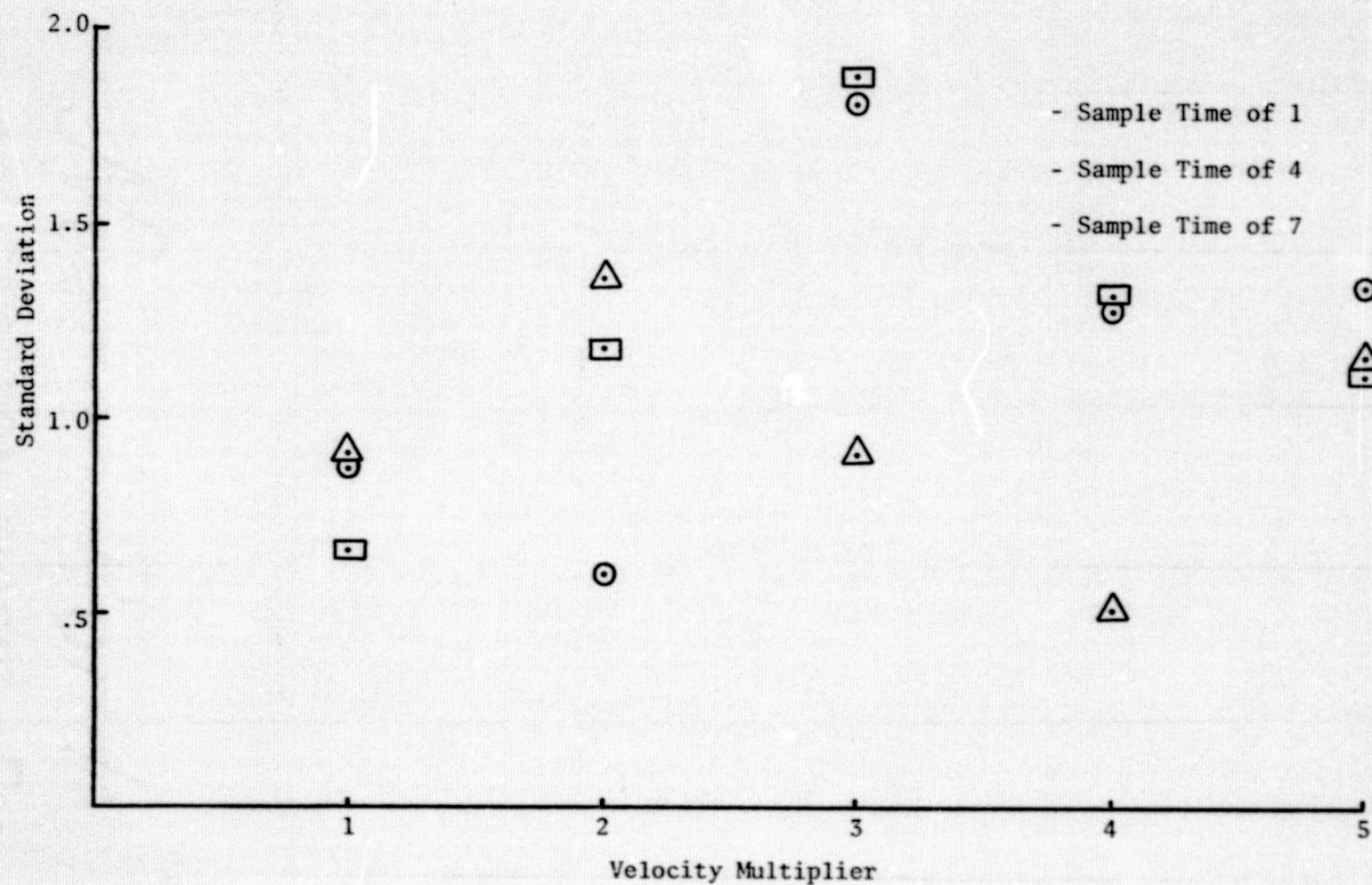


Figure F.6. Standard Deviation versus Velocity Multiplier for Tin Selenide Deposited at Ten Hertz/Sec